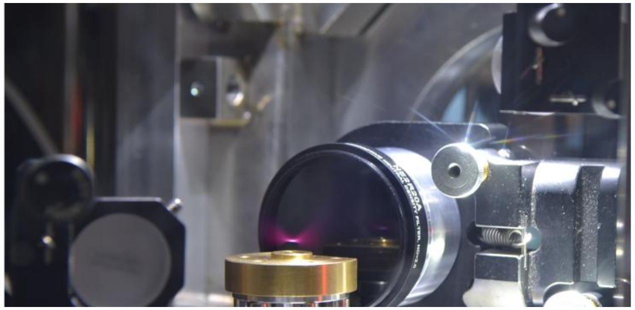
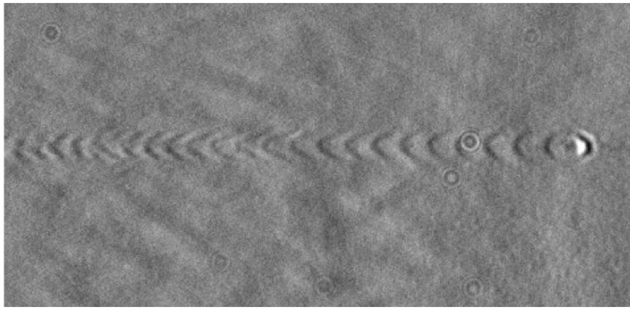
Optical probing of a laser-driven electron accelerator

seit 1558

A. Sävert, S.P.D. Mangles, E. Siminos, M. Schnell, J.M. Cole, M. Leier, M. Reuter, M.B. Schwab, M. Möller, K. Poder, G.G. Paulus, S. Skupin, Z, Najmudin, M.C. Kaluza

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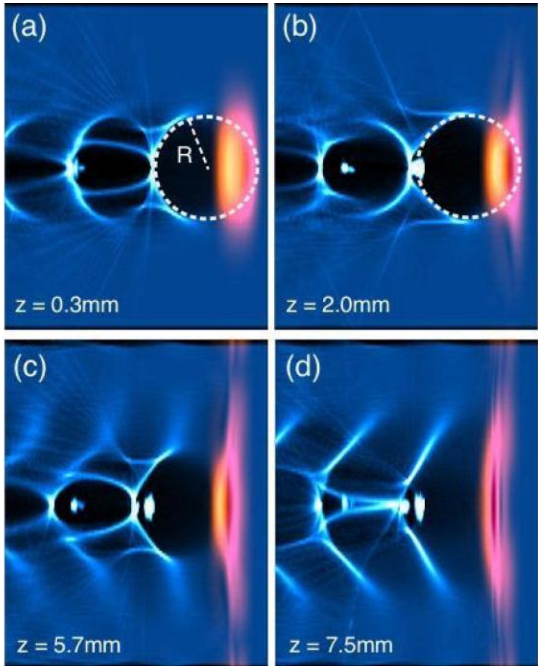
The John Adams Institute for Accelerator Science, Imperial College London
Max Planck Institute for the Physics of Complex Systems, Dresden

mpipks

2nd EAAC, Elba, 17.09.2015

Laser Wake Field Acceleration



W. Lu *et al.,* PRSTAB **10,** 061301 (2007)

Laser Wake Field Acceleration :

Tajima, Dawson, Phys. Rev. Lett. 43, 267 (1979)

→ light intensities > 10^{18} W/cm^2

Bubble/ Blowout regime:

A. Pukhov, J. Meyer-ter-Vehn, Appl. Phys. B 74, 355 (2002)

→ acceleration field > 100 GV/m

Electron bunch energy:

W. Leemans, et *al*. Phys. Rev. Lett 113, 234002 (2014) ***E= 3-4 GeV***

typically ***E= 200 MeV – 1.5 GeV***

Electron bunch duration:

O. Lundh, et *al*. Nature Physics 7, 219 (2011) ***τ_p= (4,4) fs***

A. Buck, et *al*. Nature Physics 7, 543 (2011) ***τ_p= (5,8±2,1) fs***

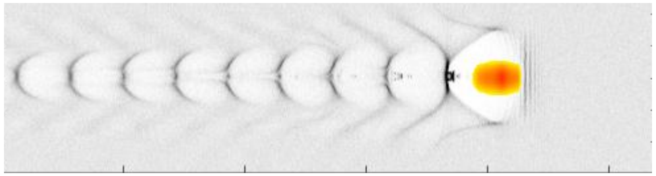
Transverse electron bunch size:

M. Schnell, et *al.* Phys. Rev. Lett. 108, 075001 (2012) ***< (1,6±0,3) µm***

Plateau, et al. Phys. Rev. Lett. 109, 064802 (2012) ***ca. 0.1 µm***

Probing laser wakefield accelerators

Challenge: Imaging a tiny, fast moving object.

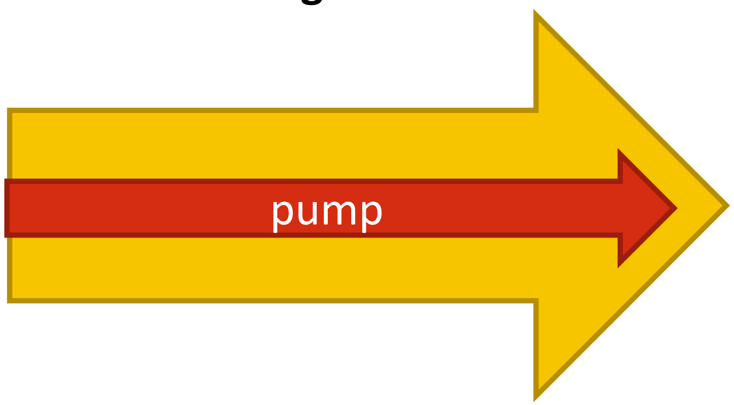


- characteristic length scale: $\lambda_p = \frac{2\pi c}{\omega_p}$

⟶ sufficient probe bandwidth

- group velocity of driver: $\sim$c

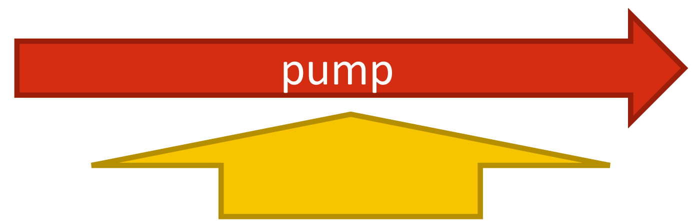
- **longitudinal**



- time integrated
- for slowly evolving plasma features

Fourier Domain Holography, …

- **transversal**

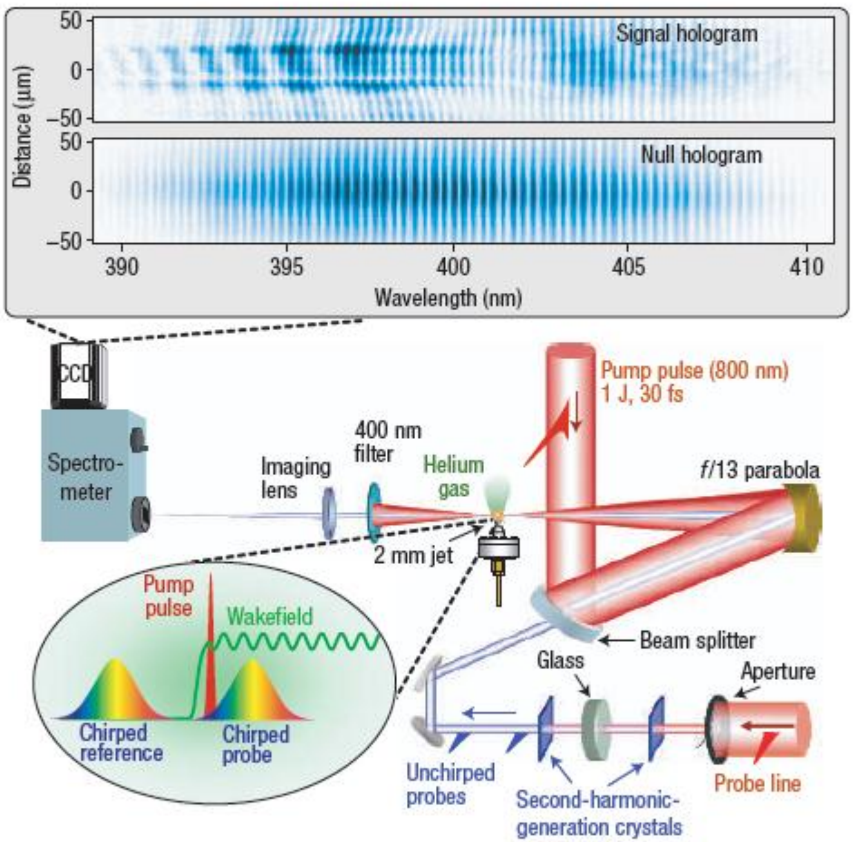


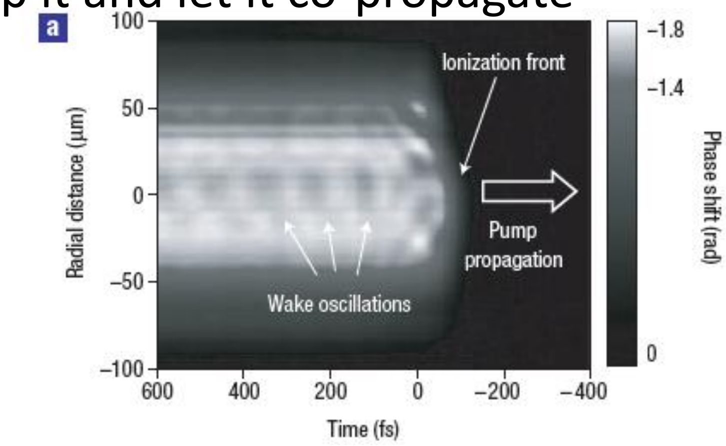
- snap shots: $\tau_{probe} \ll \lambda_p/c$
- for fast evolving plasma features

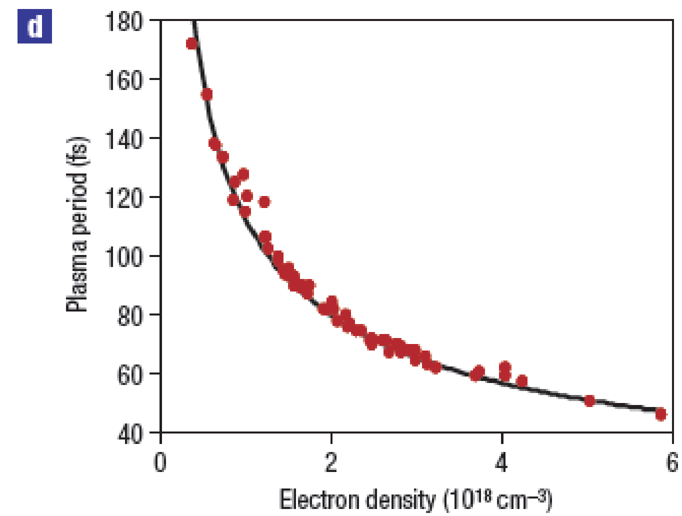
Interferometry, Shadowgraphy, Polarimetry, …

Frequency Domain Holography

Split off part of the compressed main pulse, chirp it and let it co-propagate

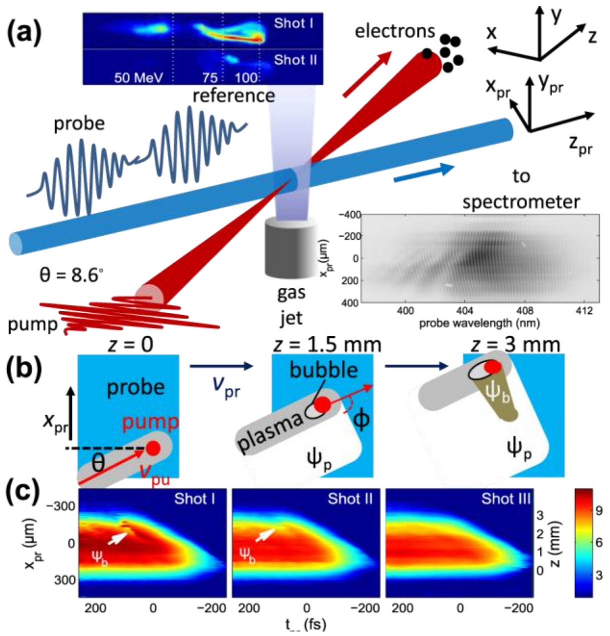


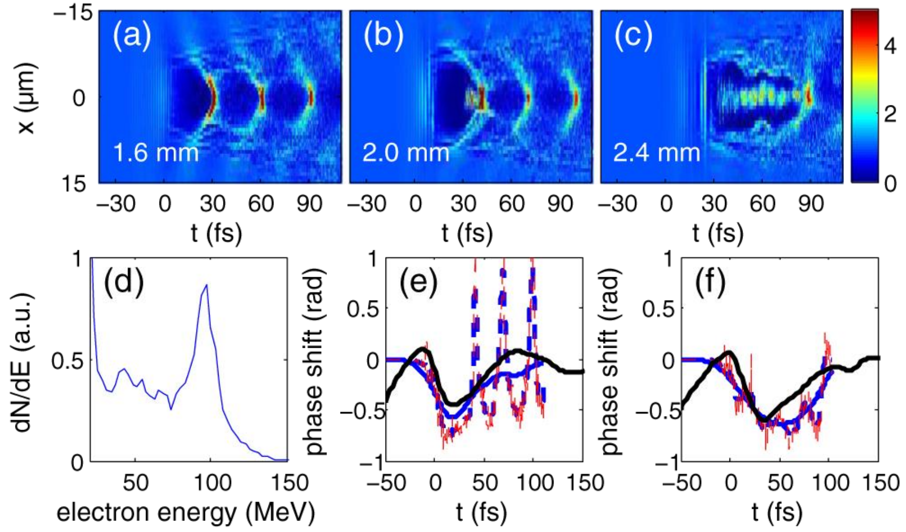




N. Matlis *et al.,* Nature Physics **2,** 749 (2006)

Frequency Domain Streak Camera

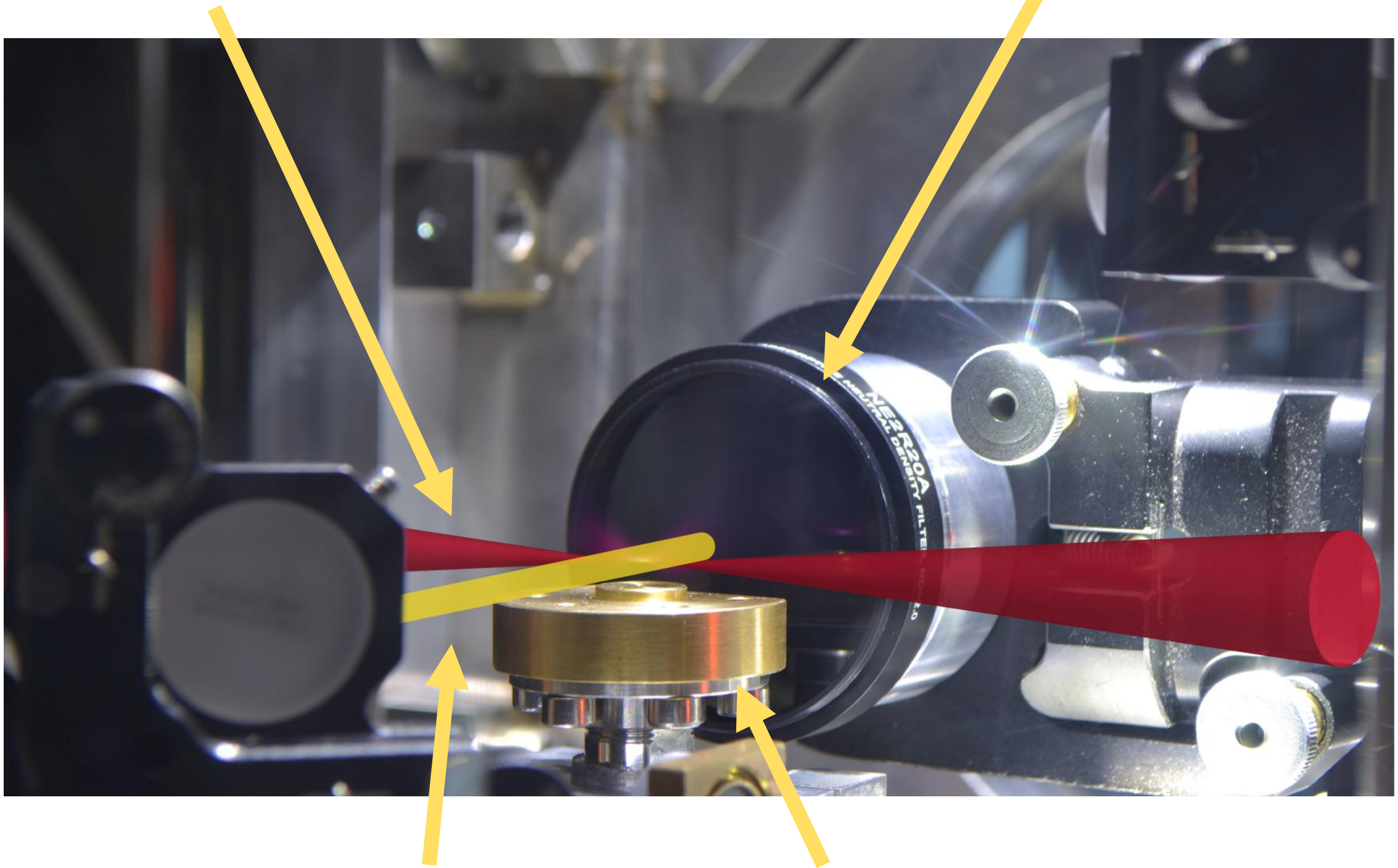




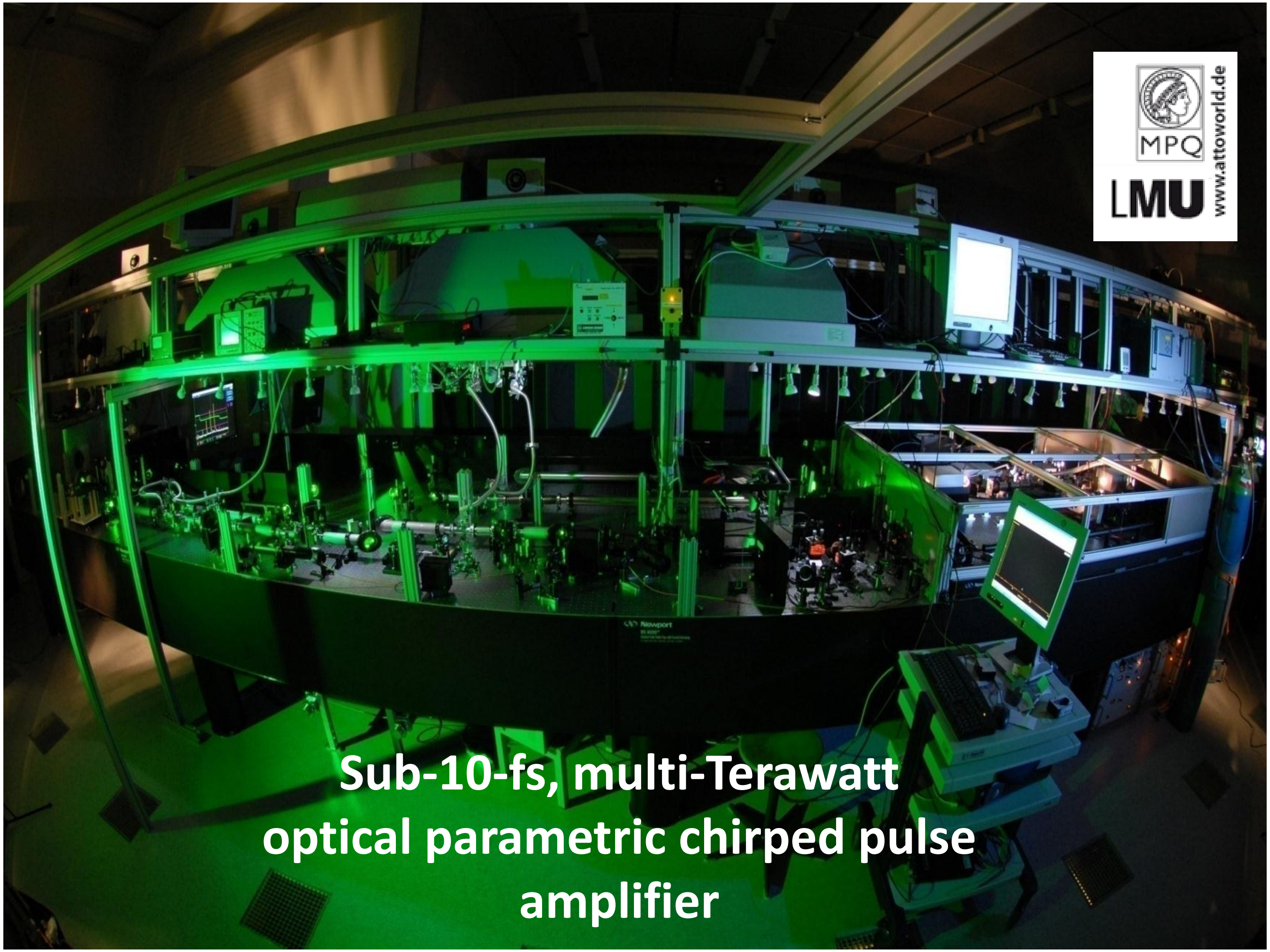
Temporal resolution depends on probe pulse bandwidth : $\tau_{probe} \cdot c > \frac{\lambda_p}{2}$

Z. Li *et al.,* Phys. Rev. Lett. **113** 085001 (2014)

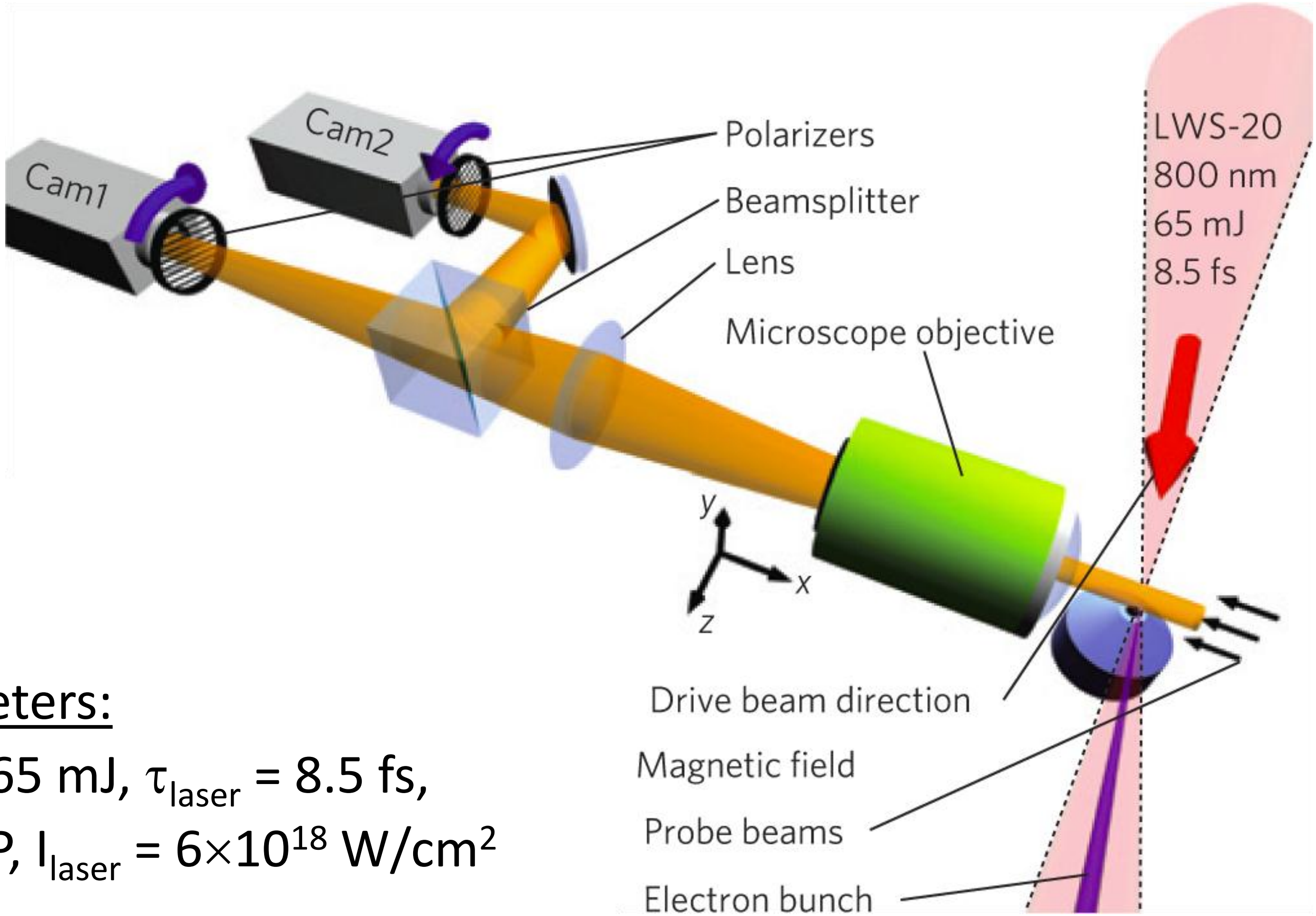
Transverse probing



Light Wave Synthesizer -20



Experimental setup – LWS 20



<u>parameters:</u>

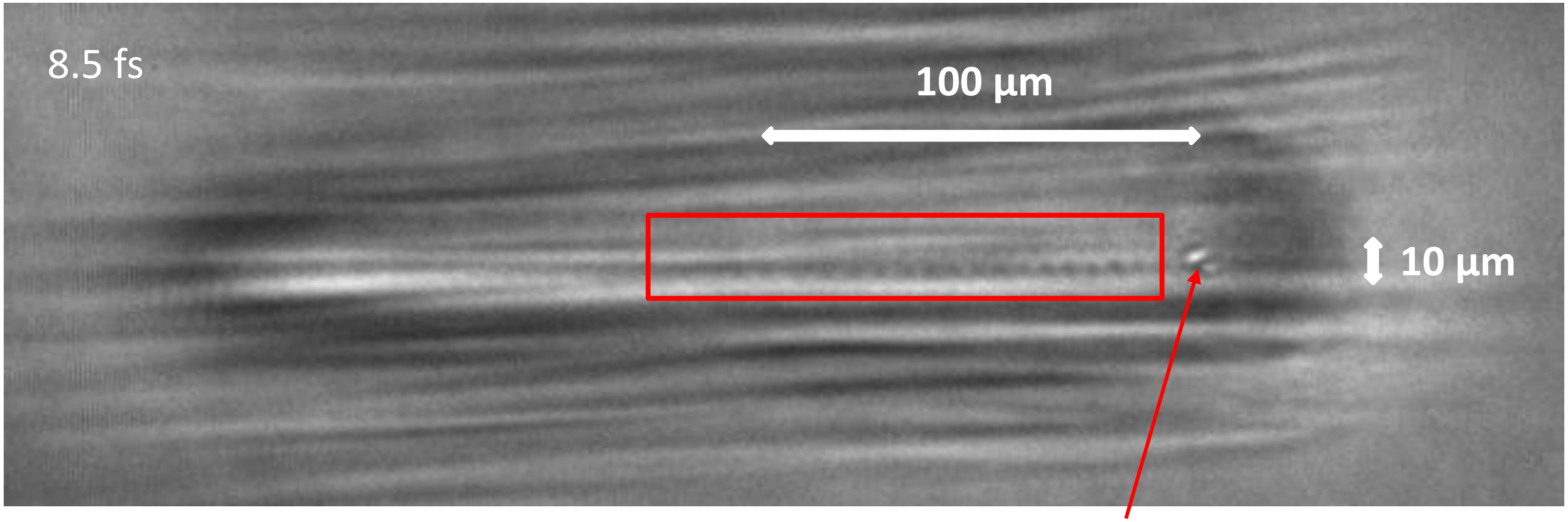
E_{laser} = 65 mJ, τ_{laser} = 8.5 fs,
f/6 OAP, $I_{laser} = 6\times10^{18}$ W/cm^2

<u>probe pulse:</u>

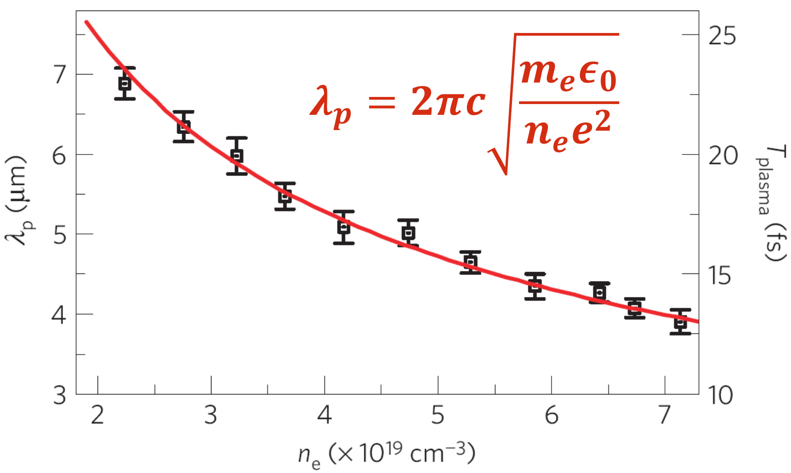
τ_{probe} = 8.5 fs @ 1ω, 2µm imaging resolution

A. Buck *et al.*, Nature Physics **7**, 543–548 (2011)

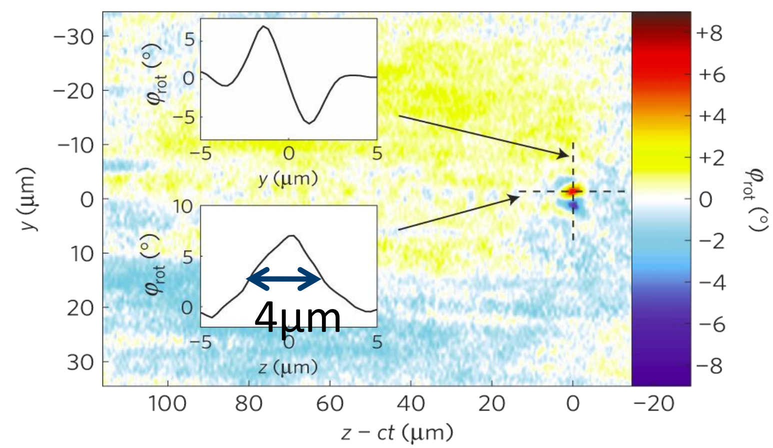
LWS 20 shadowgraphy - sub 9fs probe



Shadowgraphy
visualize e-bunch via associated B-fields

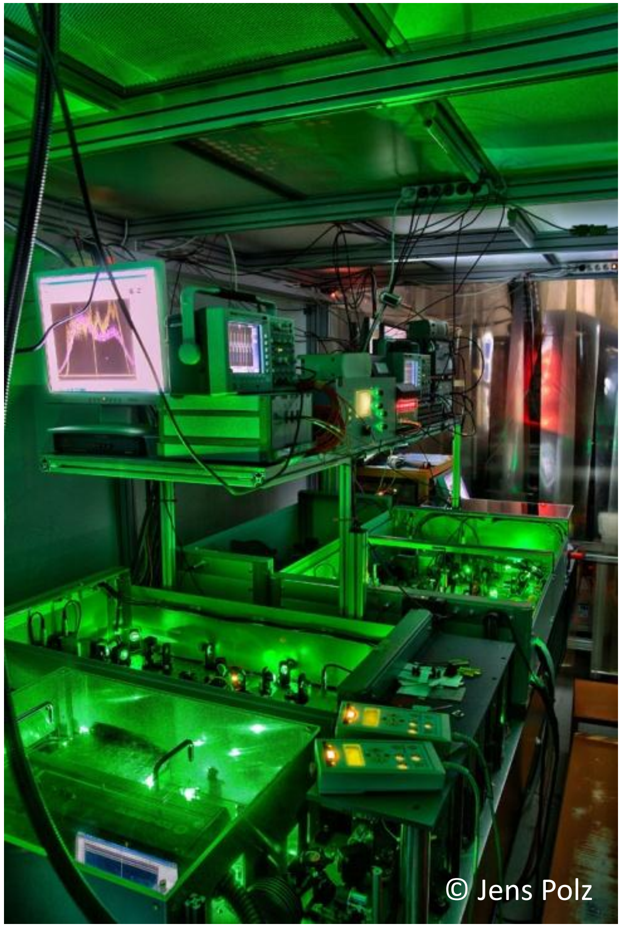


Polarimetry
visualize e-bunch via associated B-fields



A. Buck *et al.*, Nature Physics **7**, 543–548 (2011)

JETi40 laser system @ IOQ FSU Jena



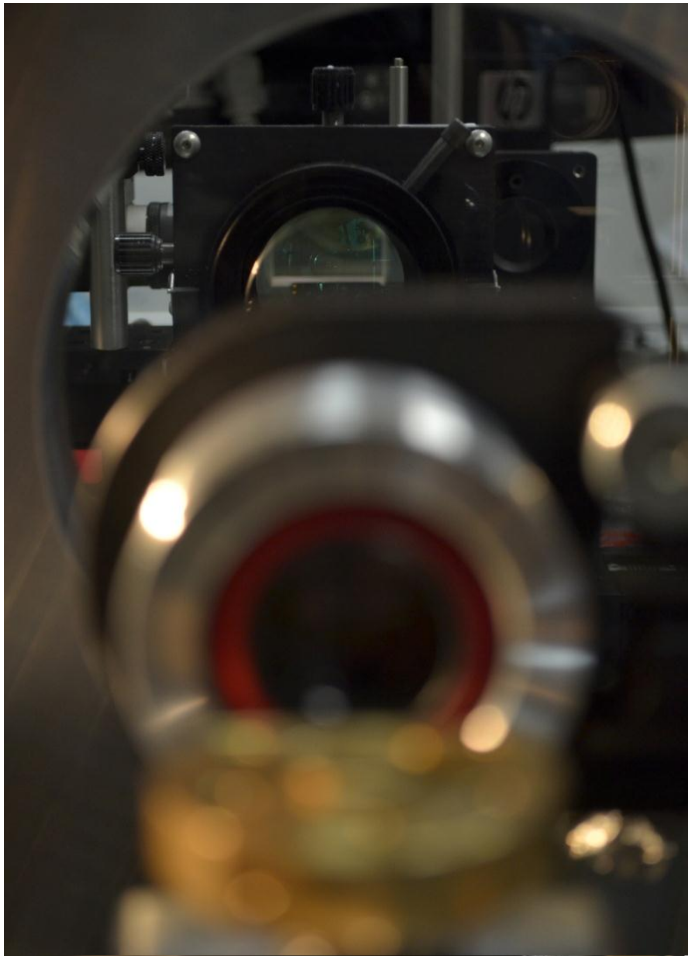
Frontend of the JETi laser

Power amplifier of the JETi laser

27 fs, 800 mJ, (30 TW peak power), 5×10^{20} W/cm^2 peak intensity, 10 Hz

Few cycle microscopy

High resolution imaging system

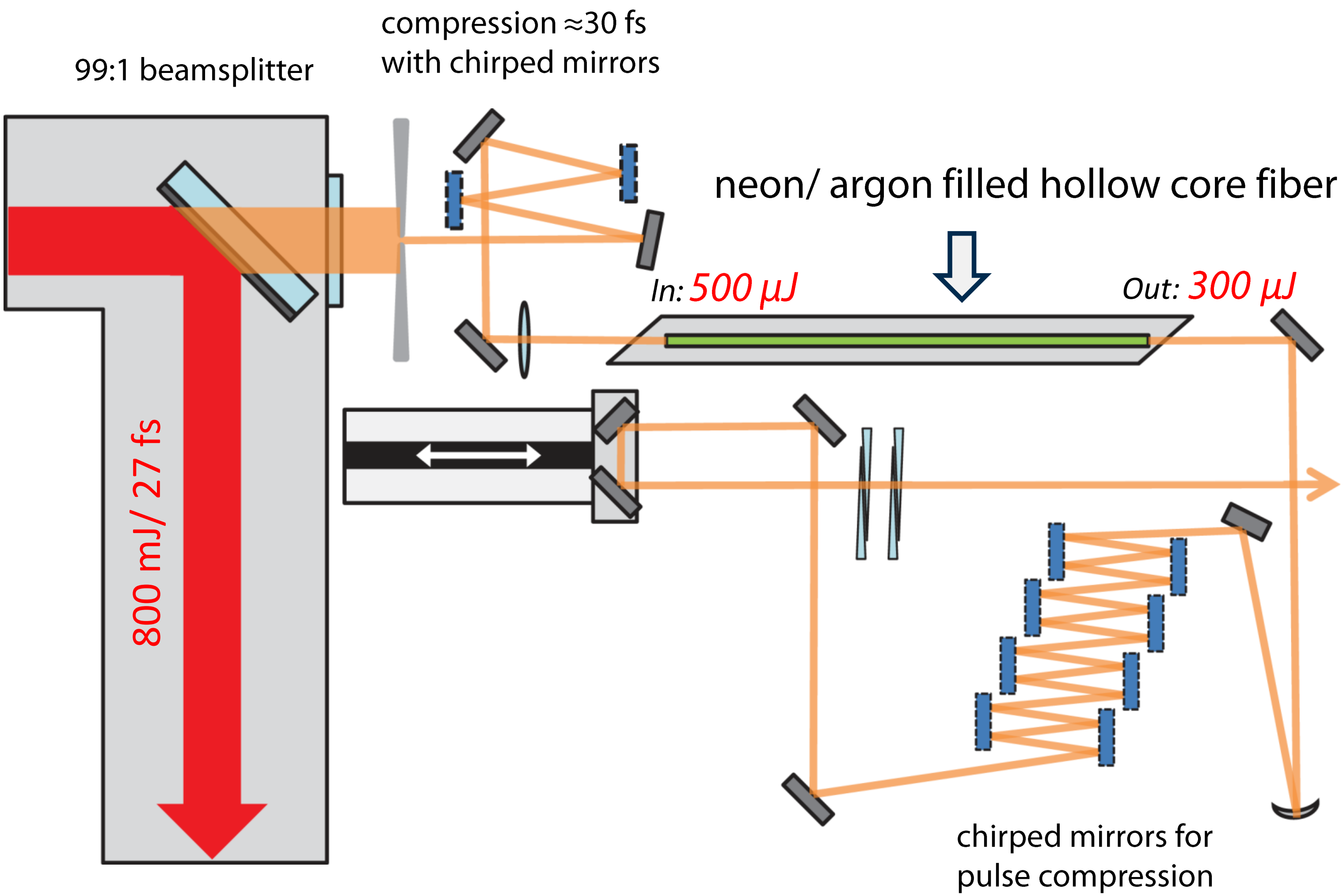


Achromatic Doublet
- focal length: 250 mm

10x Mitutoyo Plan Apo NIR Infinity-Corrected Objective
- focal length: 20 mm
- long working distance: 30 mm
- resolving power: 1.5 µm

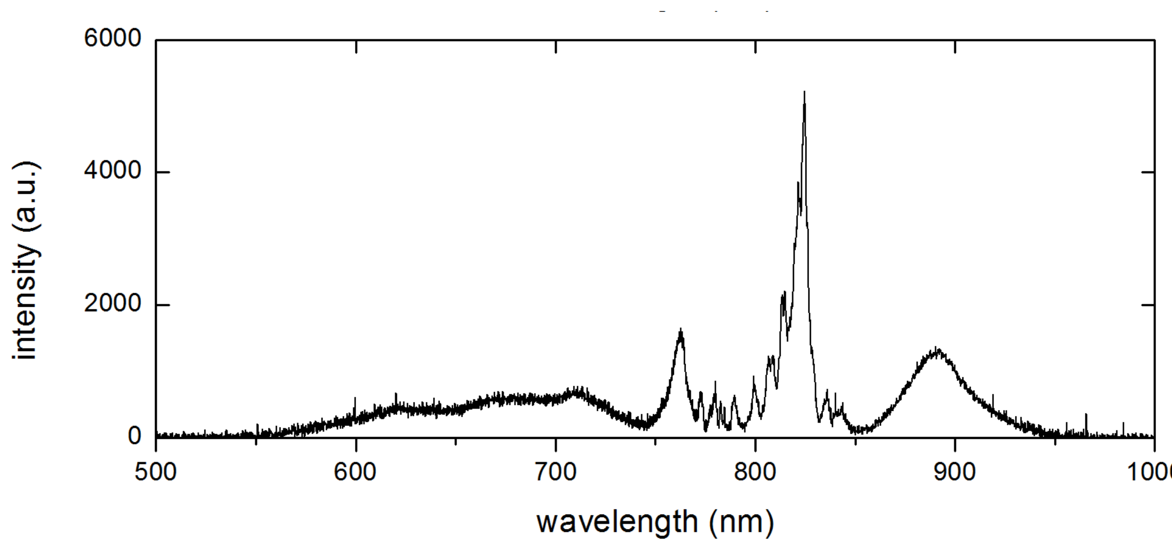
Magnification factor: 12.5
CCD pixel size: 6.4 µm

Few cycle probe beam - setup

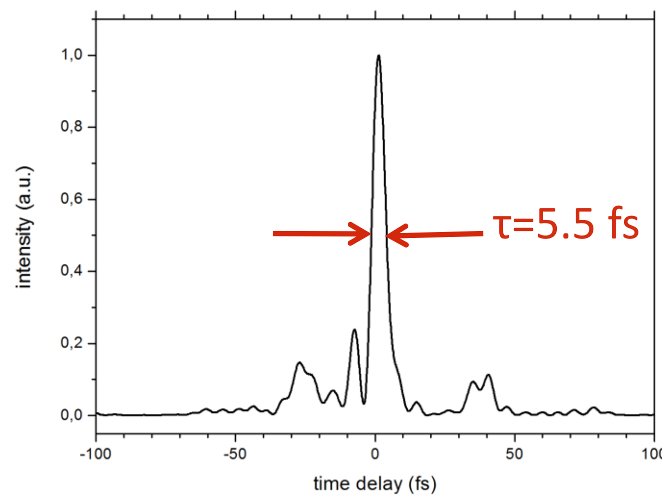


M.B. Schwab *et al.*, Applied Physics Letters **103**, 191118 (2013)

Few cycle probe beam - characterization

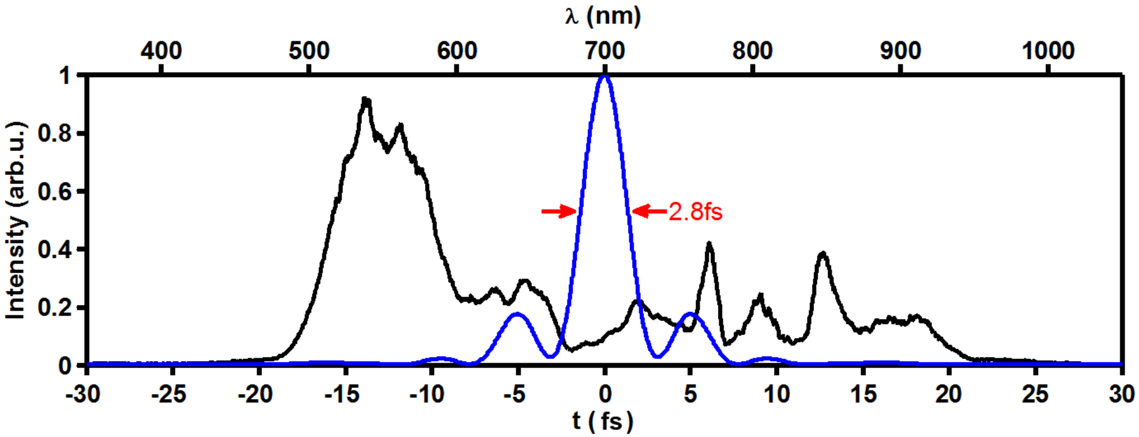


Argon @ 0.4 bar
Fourier limit: 4.4 fs



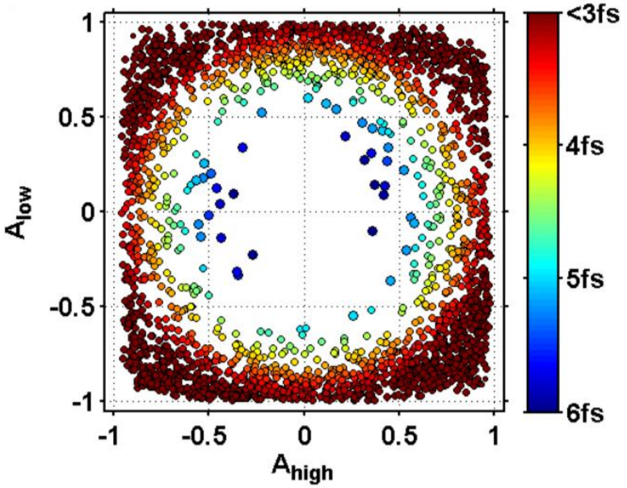
M.B. Schwab *et al.*, Applied Physics Letters **103**, 191118 (2013)

Few cycle probe beam - optimization



Stereo ATI Phasemeter to measure the asymmetry of the laser pulse

G.G. Paulus *et al.*, Nature 414, 182 (2001)

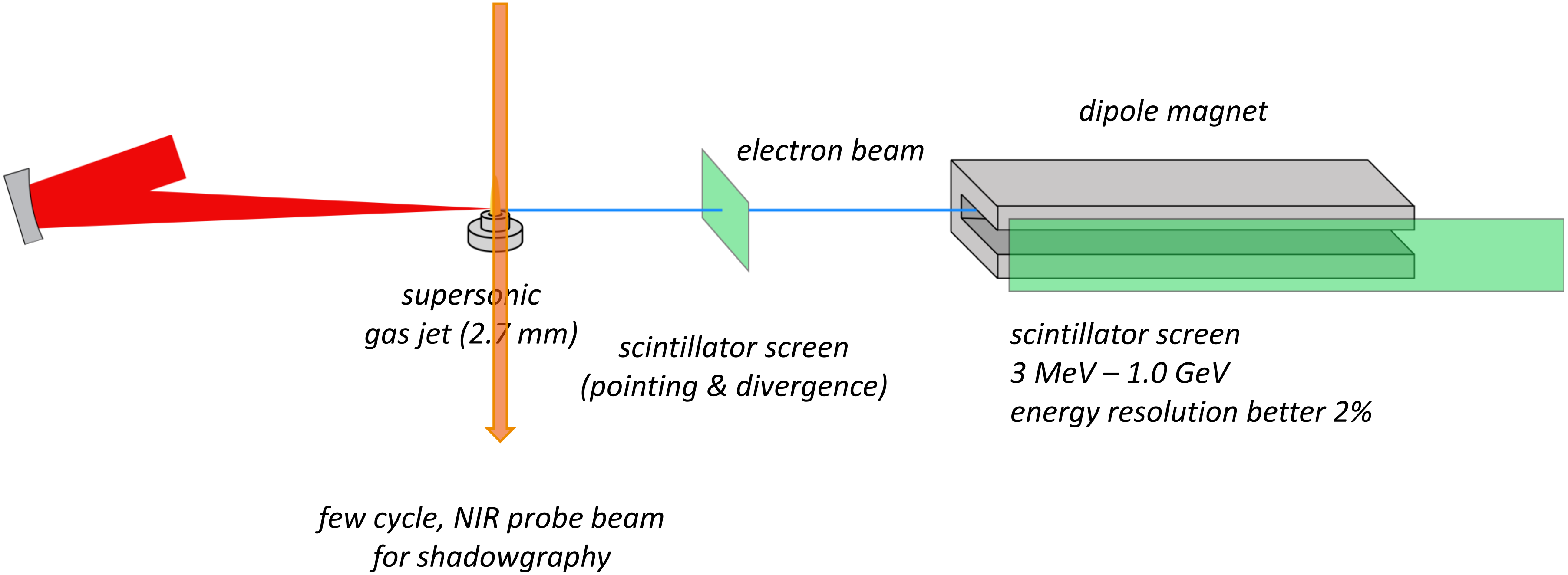


3600 subsequent shots (1h), > 86 % of shots below 4 fs

D. Adolph *et al.*, in preparation

Experimental parameters

JETi 40
35 fs, 720 mJ (24TW) laser pulse
f/13, $d_{(FWHM)}$: 11 µm, $a_0 \approx 1.7$

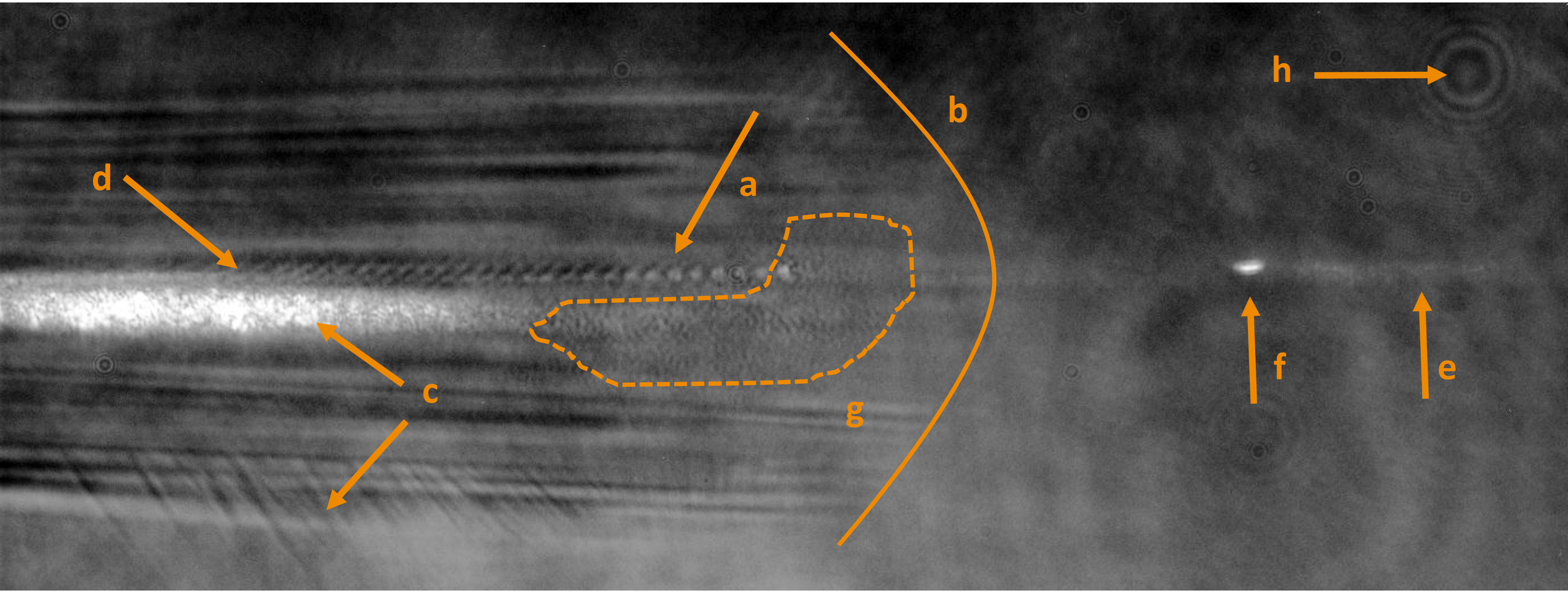


developed in cooperation with group of Axel Bernhard

KIT Karlsruher Institut für Technologie

LWFA under the microscope

Helium, 1.7x10^{19} cm^{-3}



a: plasma wave

b: ionization front

c: Raman side scattering

d: tilted plasma wave

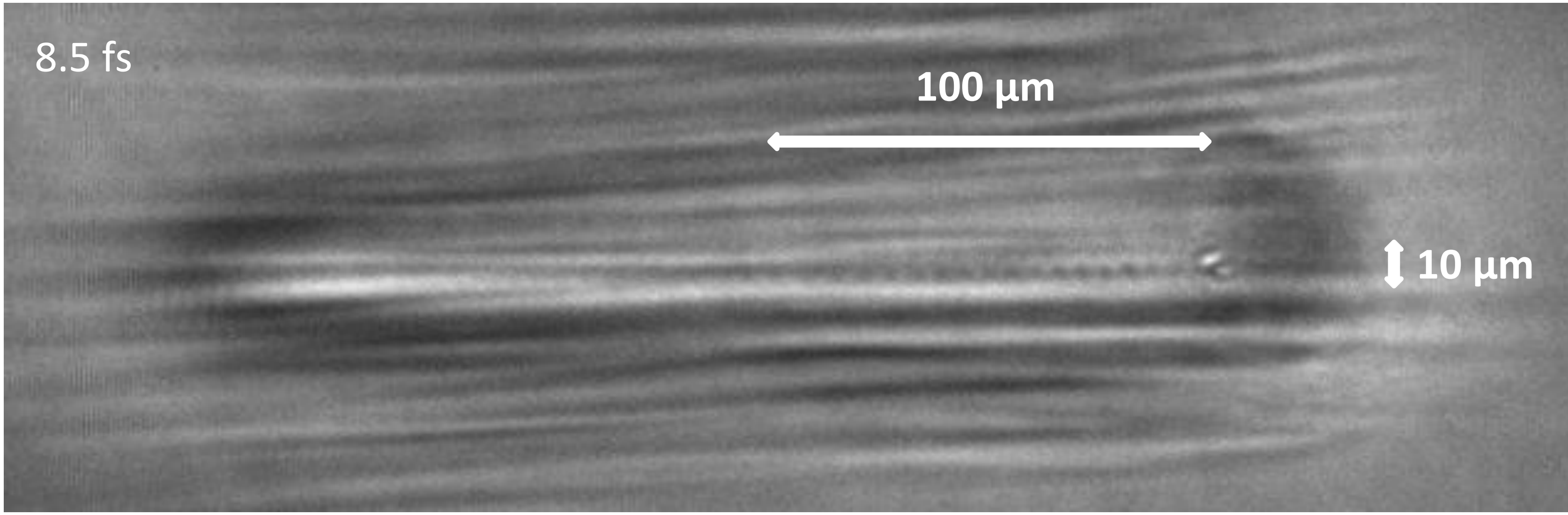
e: Thomson scattering

f: wavebreaking radiation

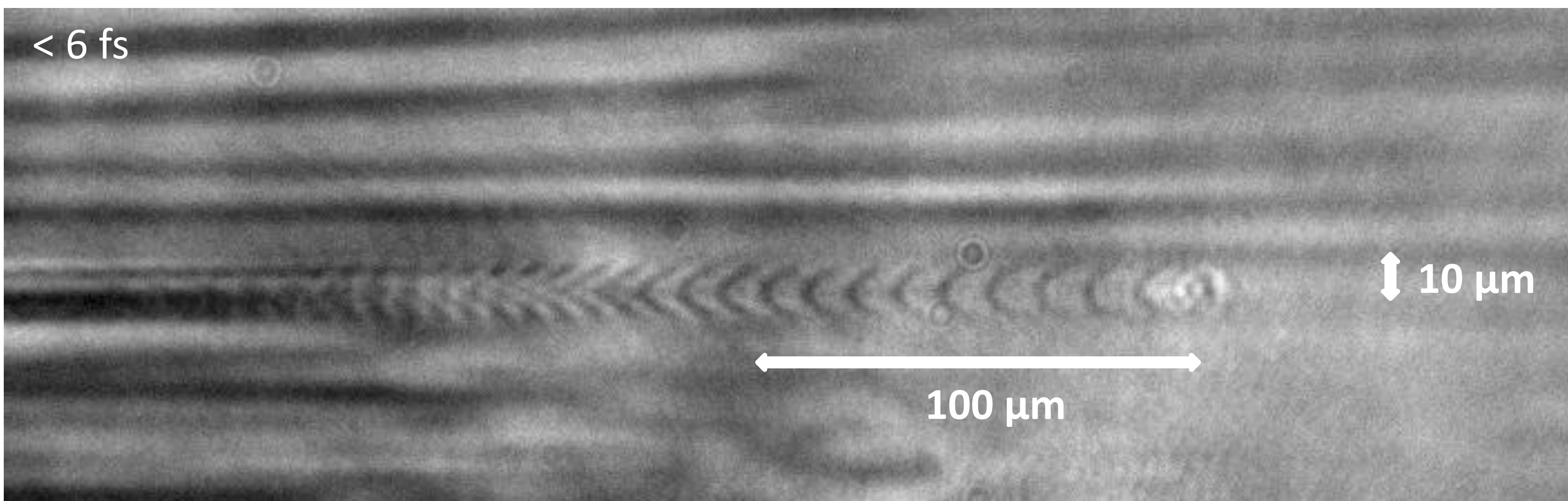
g: speckle/ noise

h: dust/ dirt

sub 9 fs vs. sub 6 fs probe pulses



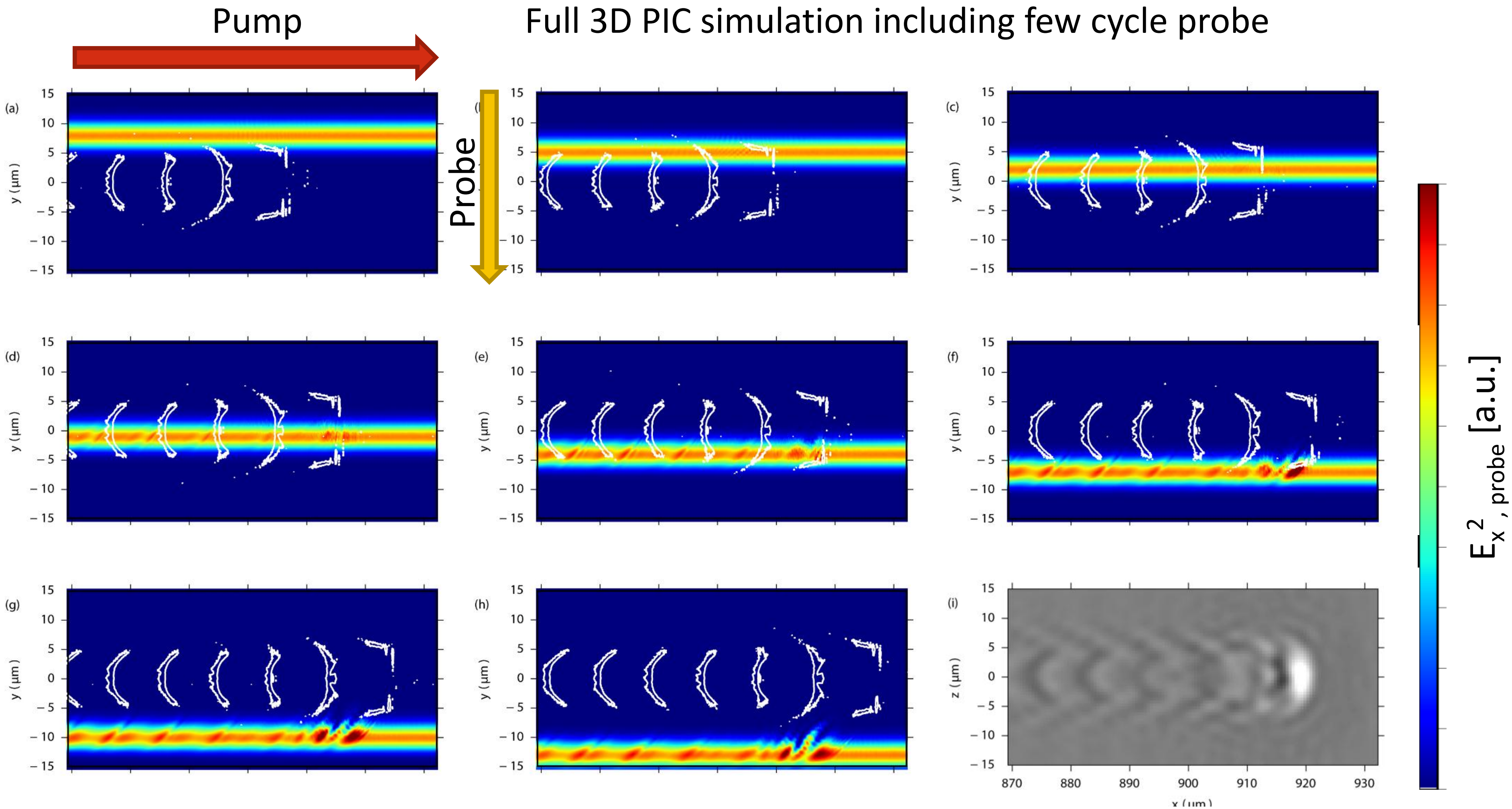
A. Buck *et al.*, Nature Physics **7**, 543–548 (2011)



A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

Tracking the probe beam – 3D simulation

Full 3D PIC simulation including few cycle probe



Simulated shadowgram
feat. imaging optics and detector

Shadowgram is formed mostly in the center part.
High gradients & short pulse duration give high contrast.

by courtesy of Evangelos Siminos
(in preparation)

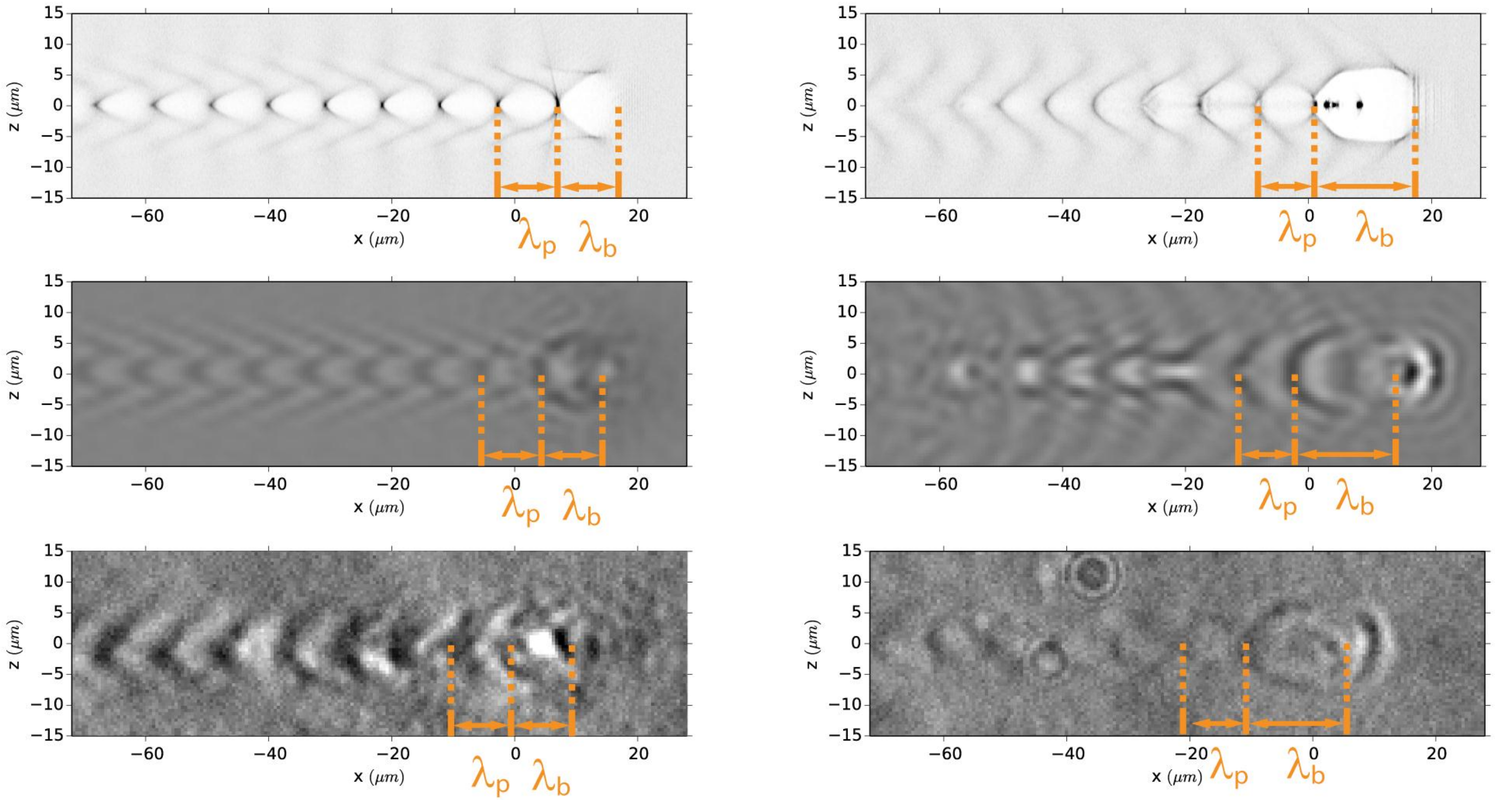
Bubble length - measurement

$v_g t$=527 µm ***$v_g t$=1214 µm***

electron density:

computed shadowgram:

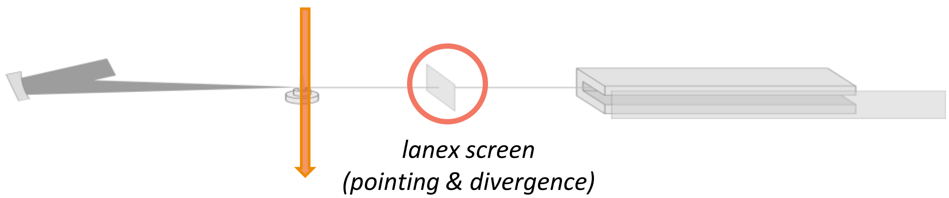
experiment:

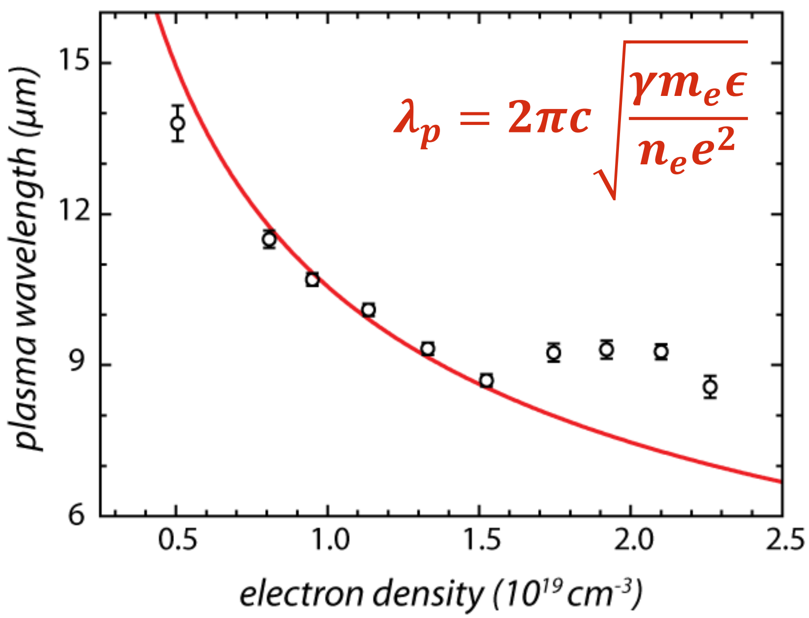


Bubble length and plasma period length are directly accessible!

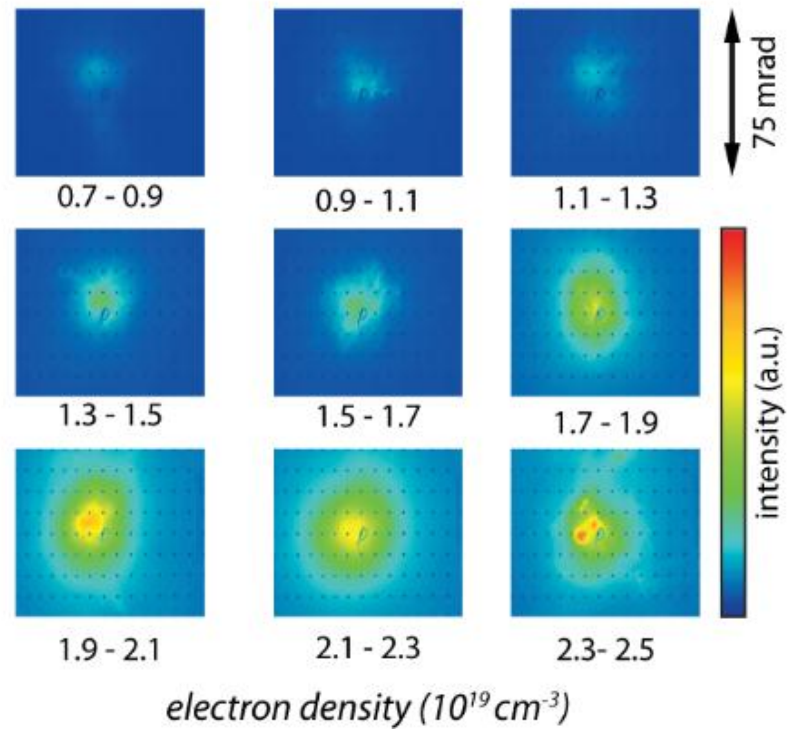
Influence of the plasma density

Results for the second plasma period





$$\lambda_p = 2\pi c \sqrt{\frac{\gamma m_e \epsilon}{n_e e^2}}$$



critical power for self trapping:

$$\frac{\alpha P}{P_c} > \frac{1}{16}\left[\ln\left(\frac{2n_c}{3n_e}\right) - 1\right]^3$$

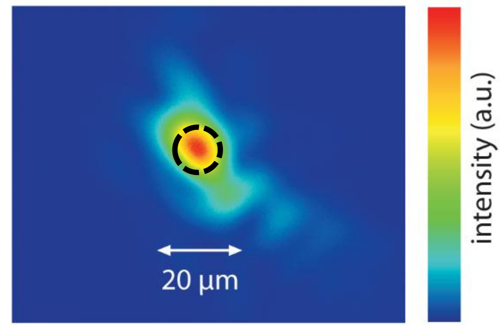
for our parameters: n_e> **1.5×10^{19}cm^{-3}**

S.P.D. Mangles *et al.* Phys. Rev. STAB **15**, 011302 (2012)
A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

Influence of the focal spot

$$\frac{\alpha P}{P_c} > \frac{1}{16}\left[\ln\left(\frac{2n_c}{3n_e}\right) - 1\right]^3$$

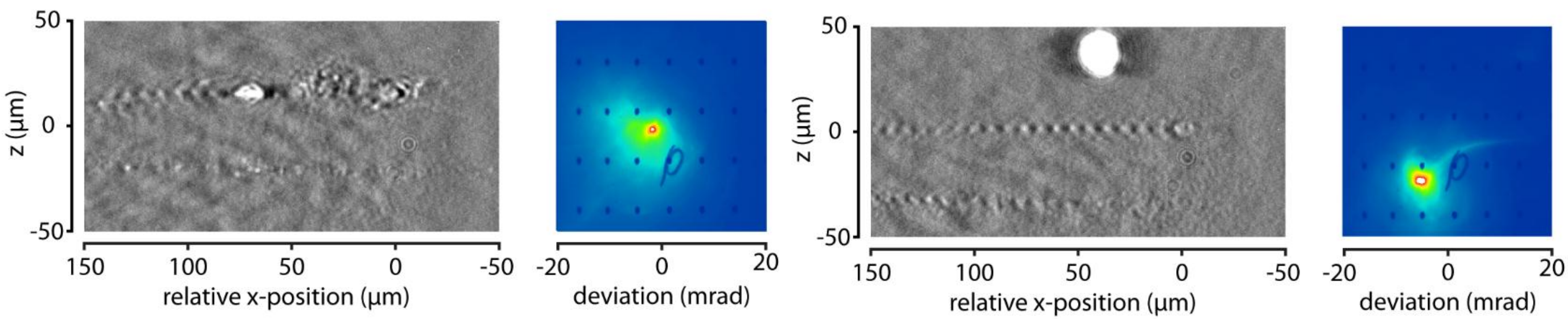
effective critical Power!



α=0.23

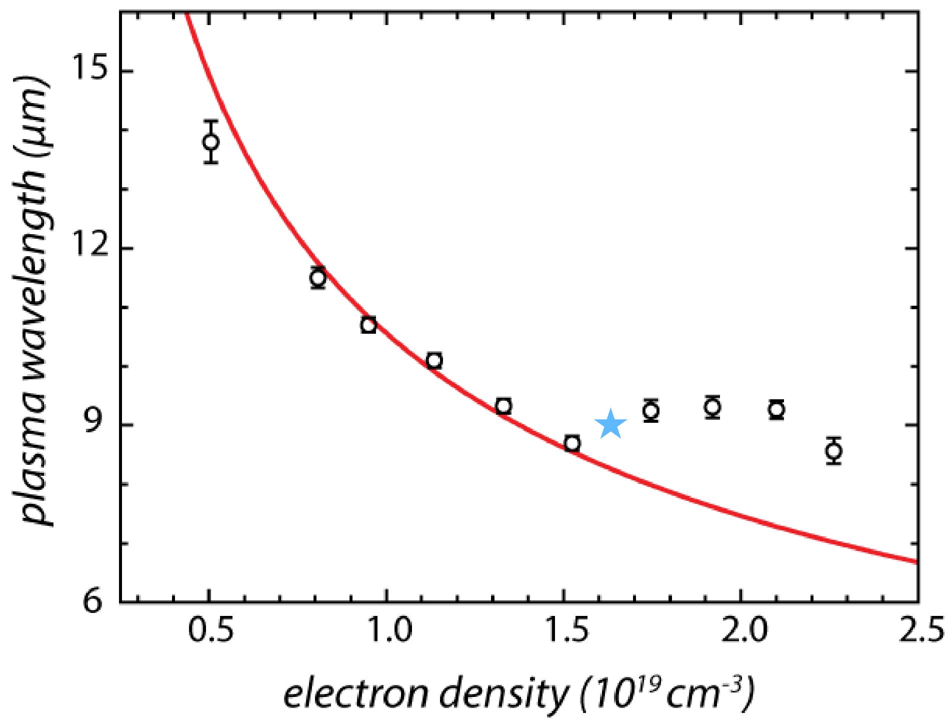
JETi40 focal spot without adaptive optic

Filamentation instability: *Helium, 2x10^{19} cm^{-3}*

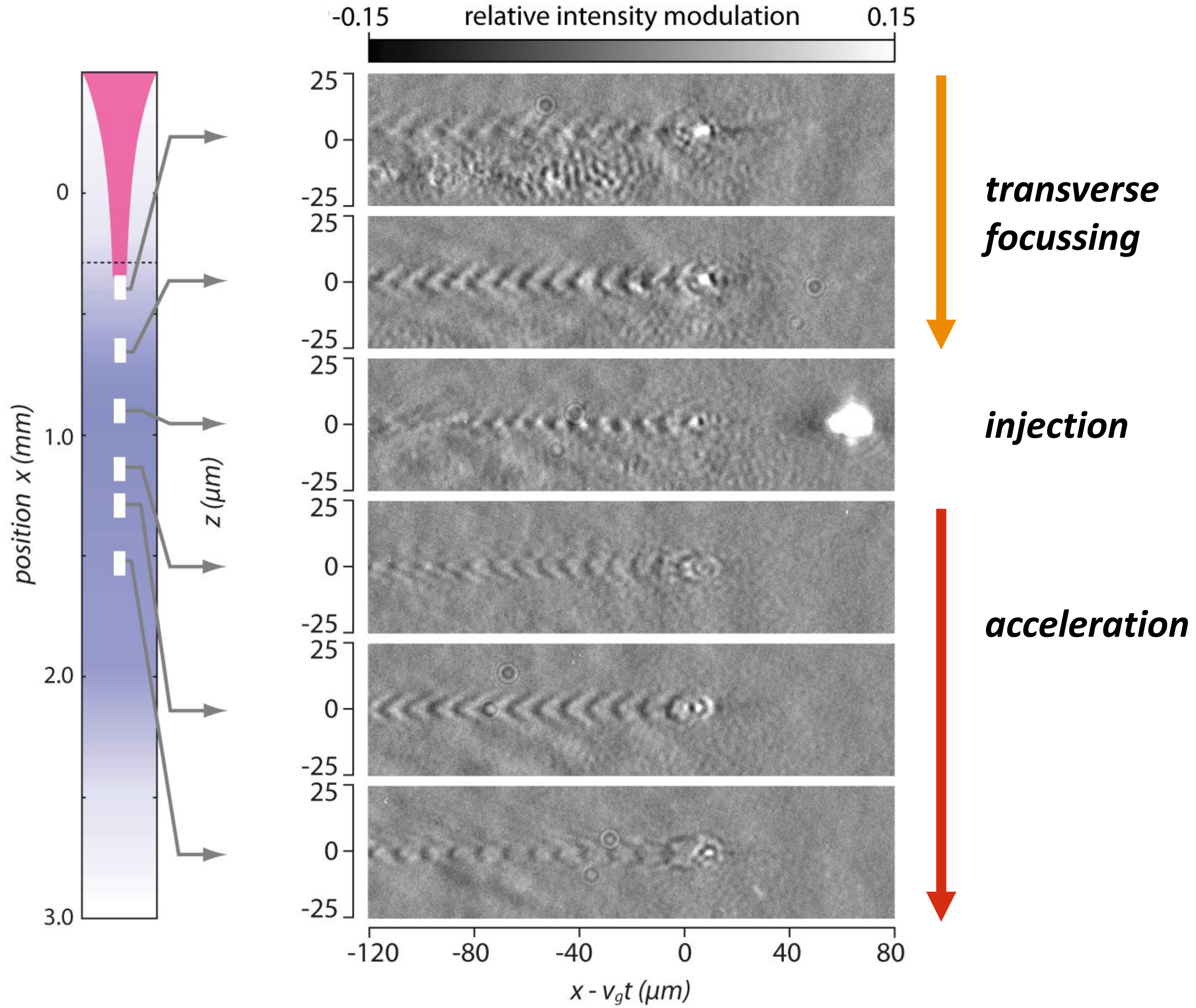


Evolution of the plasma wakefield

at the critical density for self-injection

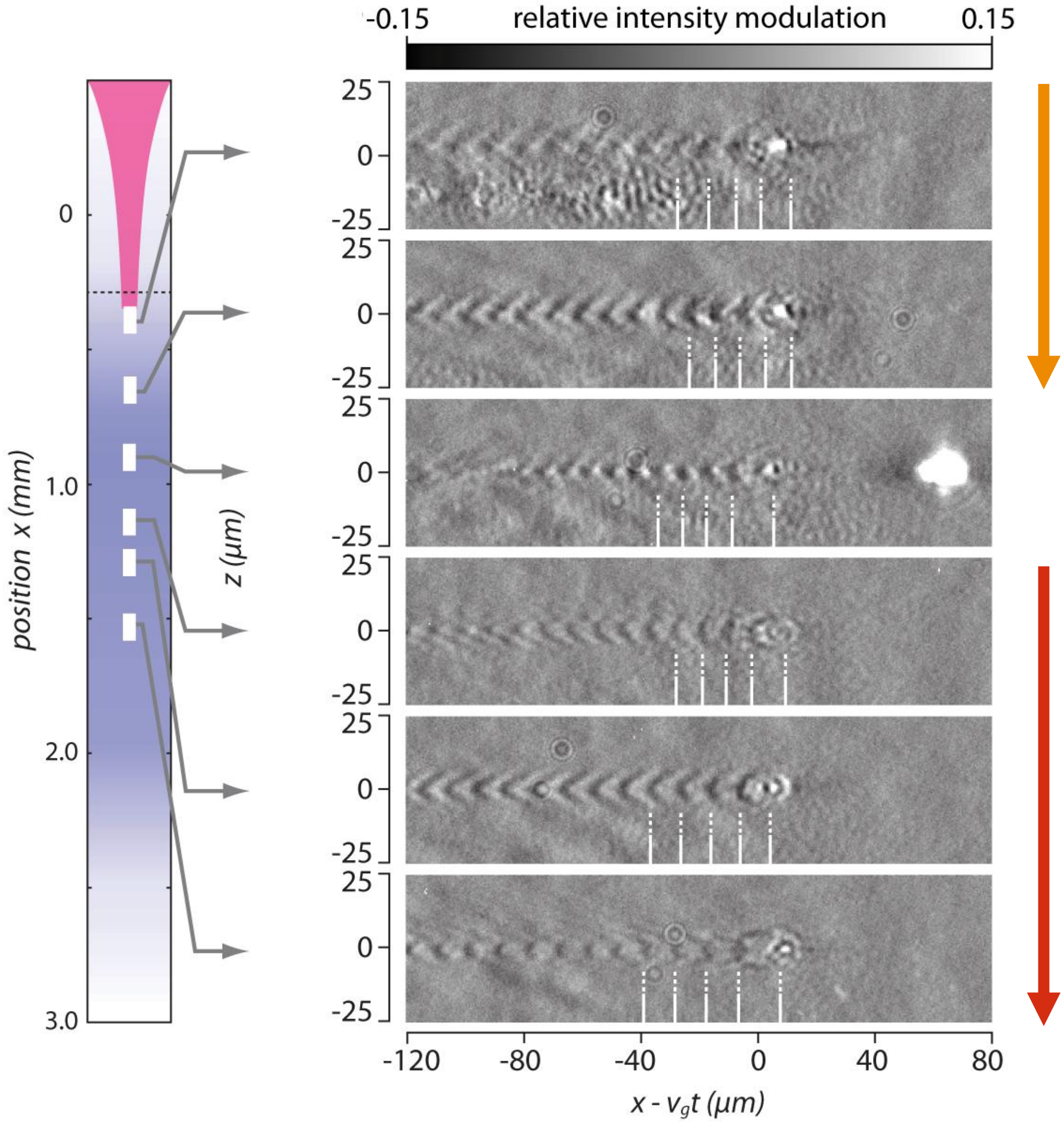


Evolution of the plasma wakefield



A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

Evolution of the plasma wakefield



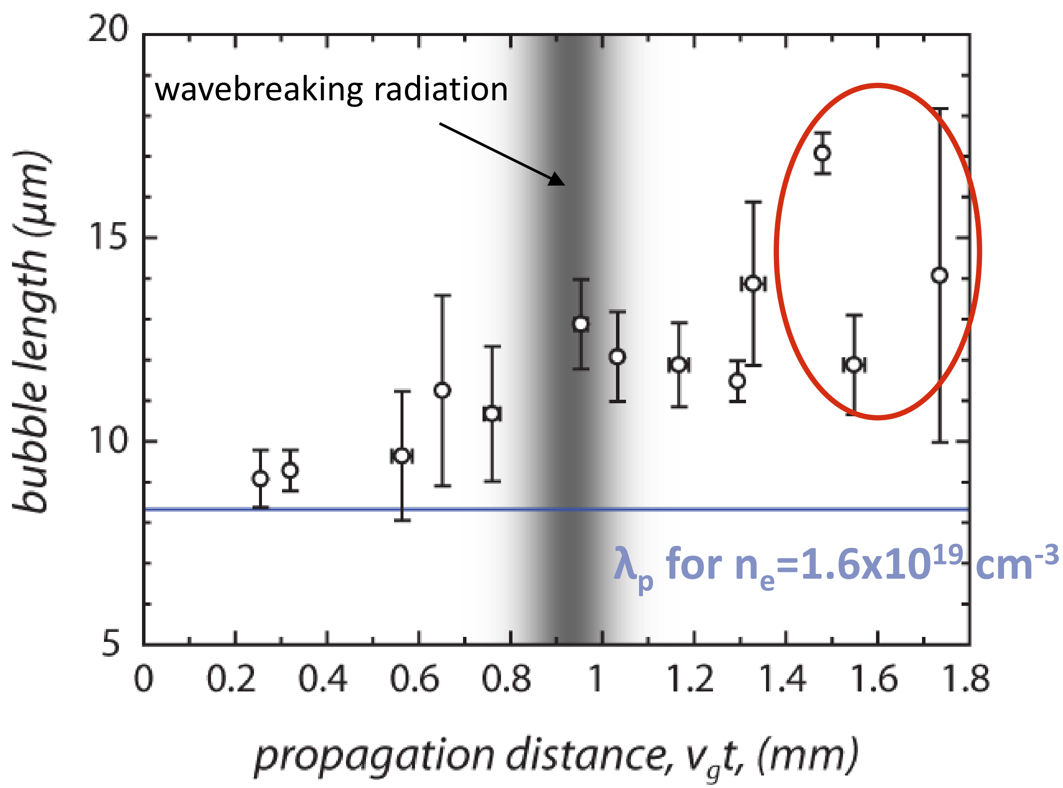
transverse focussing

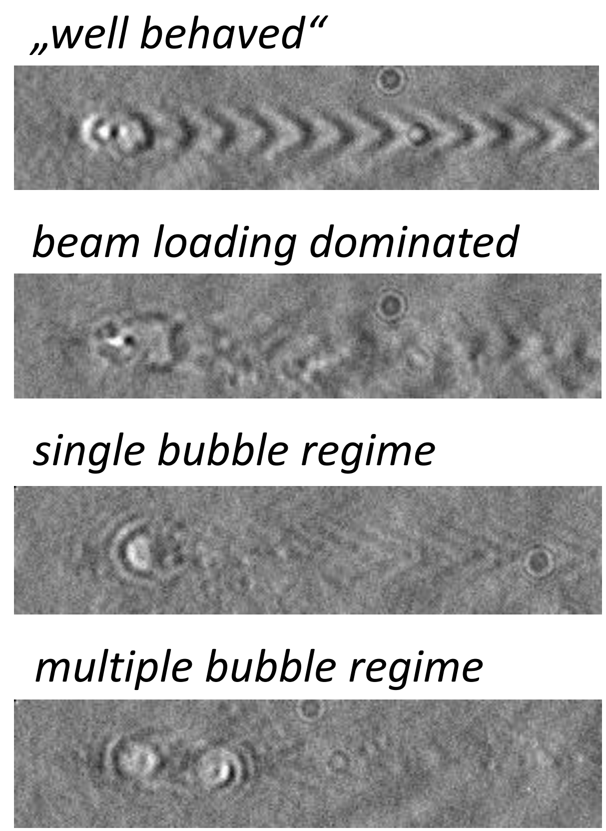
injection

acceleration

A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

Bubble dynamics - expansion



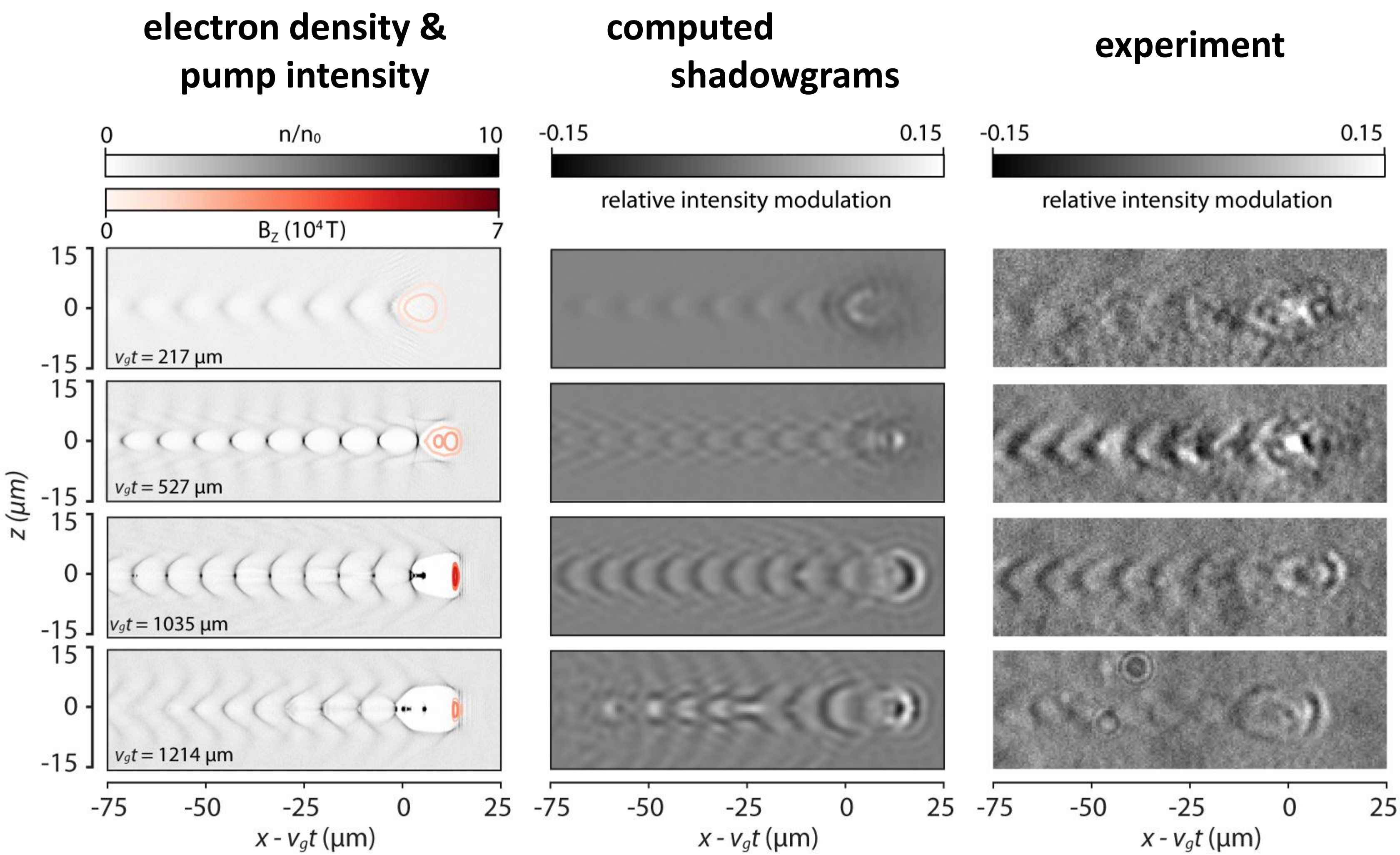


Bubble expansion starts before injection. ➡ No beamloading but amplification of the pump pulse.

$$\lambda_p^* \approx \lambda_p \left(1 + \frac{a_0^2}{2}\right)^{1/4}$$

A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

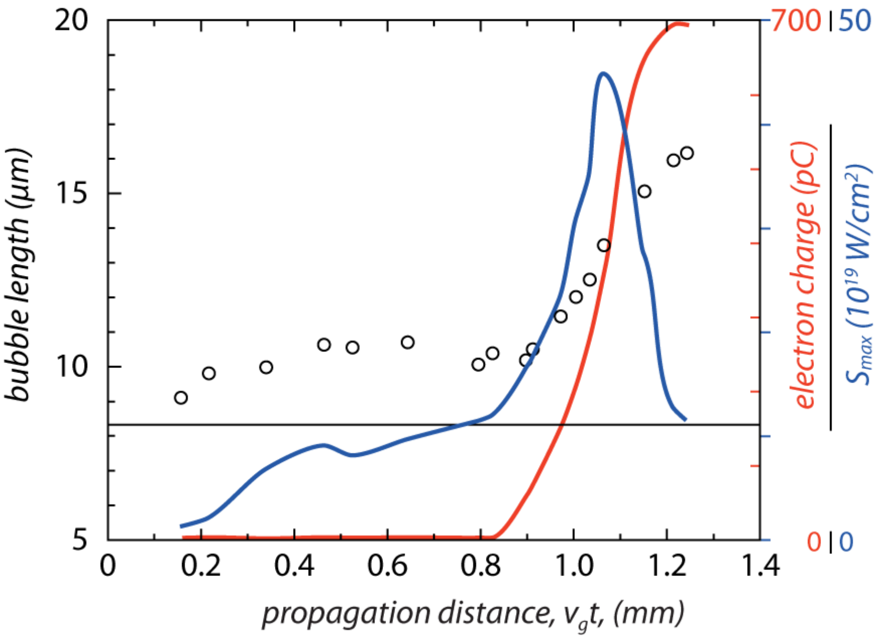
3D PIC simulation including the probe

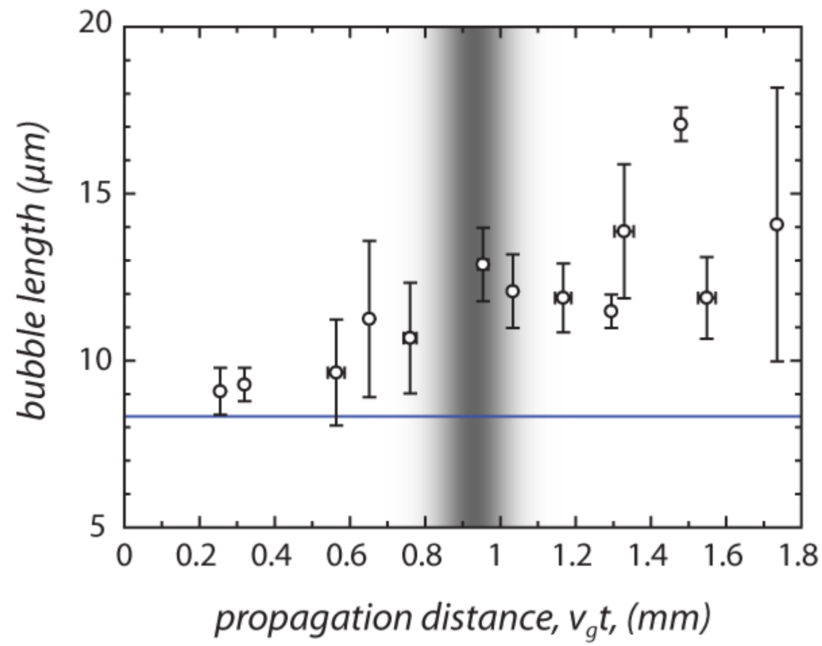


3D PIC simulation (EPOCH), 150x70x70 µm^3 sliding box
2700x525x525 cells

by courtesy of Evangelos Siminos

Bubble expansion – simulation



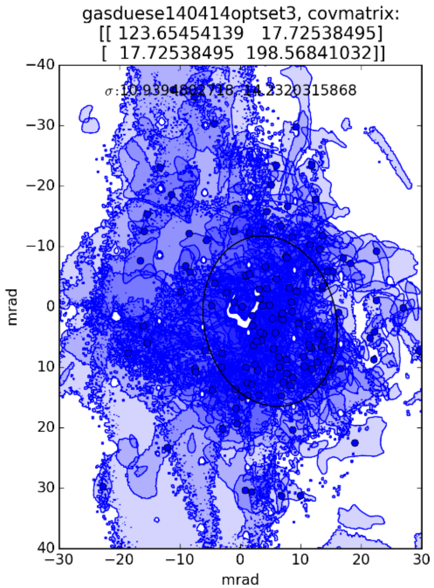


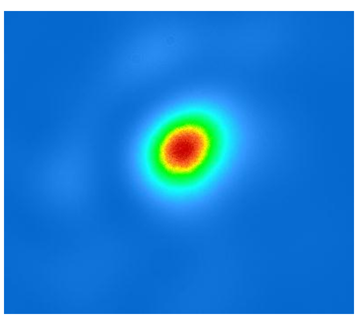
Bubble expansion starts before injection. ➡ No beamloading but amplification of the pump pulse.

A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

Stable LWFA – Ionization injection

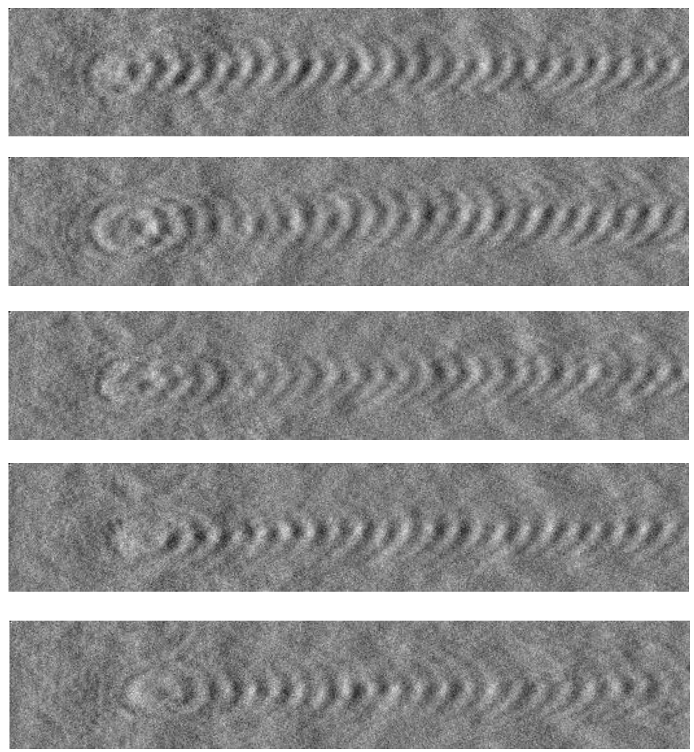
Beam pointing gas jet selfinjection





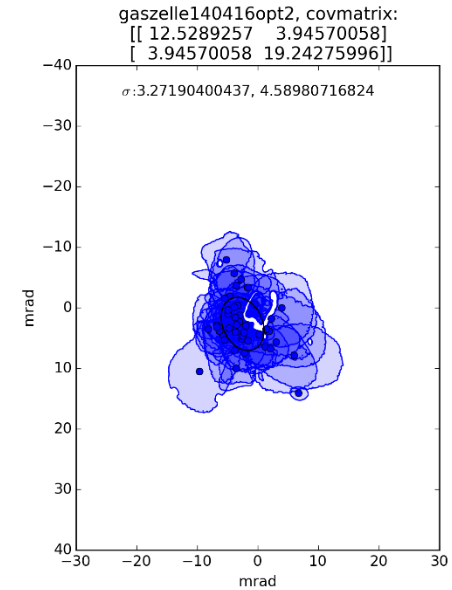
optimized laser focal spot (adaptive optic)

Gas cell



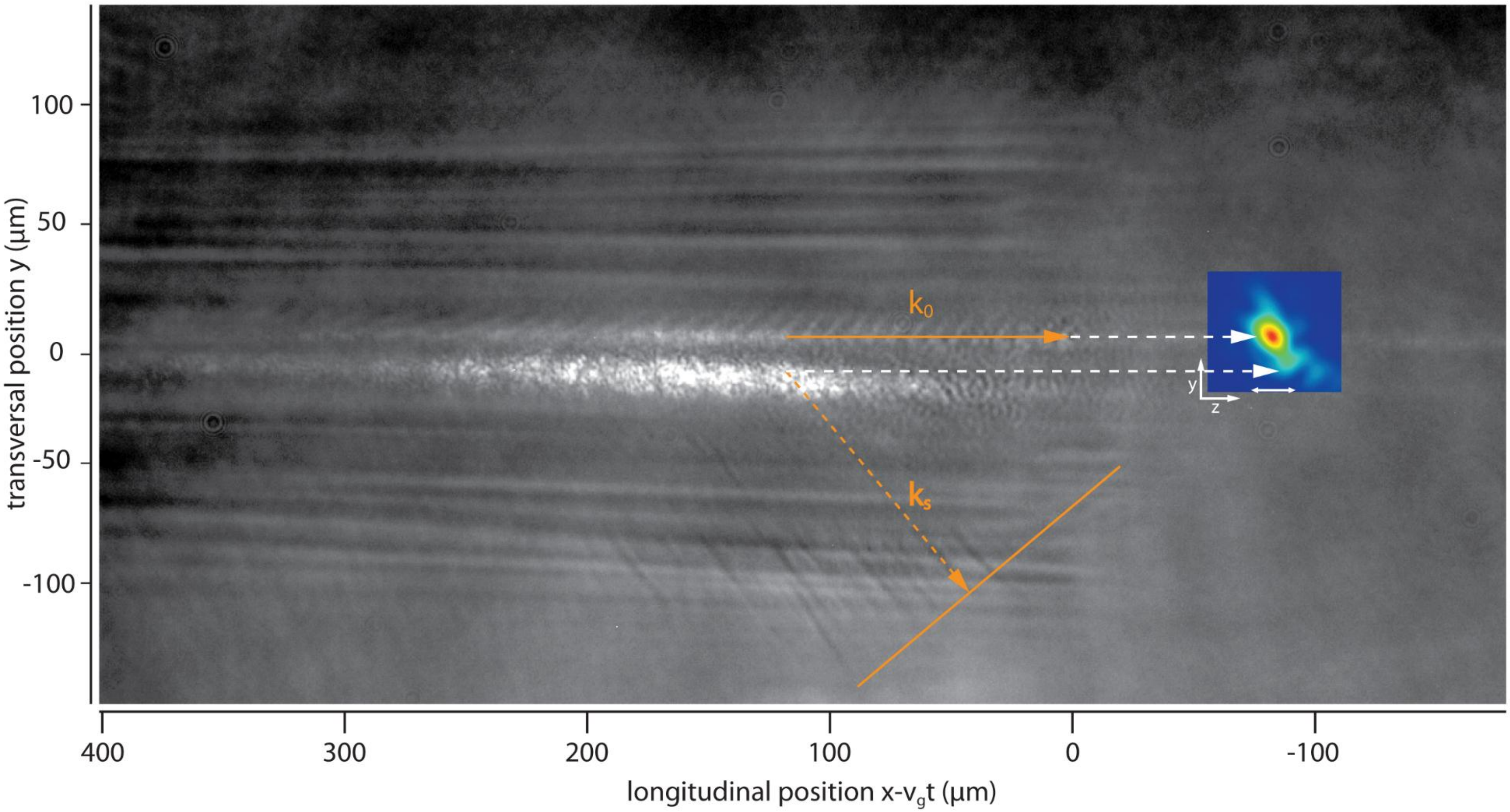
$n_e = 1 \times 10^{19}\ cm^{-3}$

Beam pointing gas cell 95% He+ 5% N_2

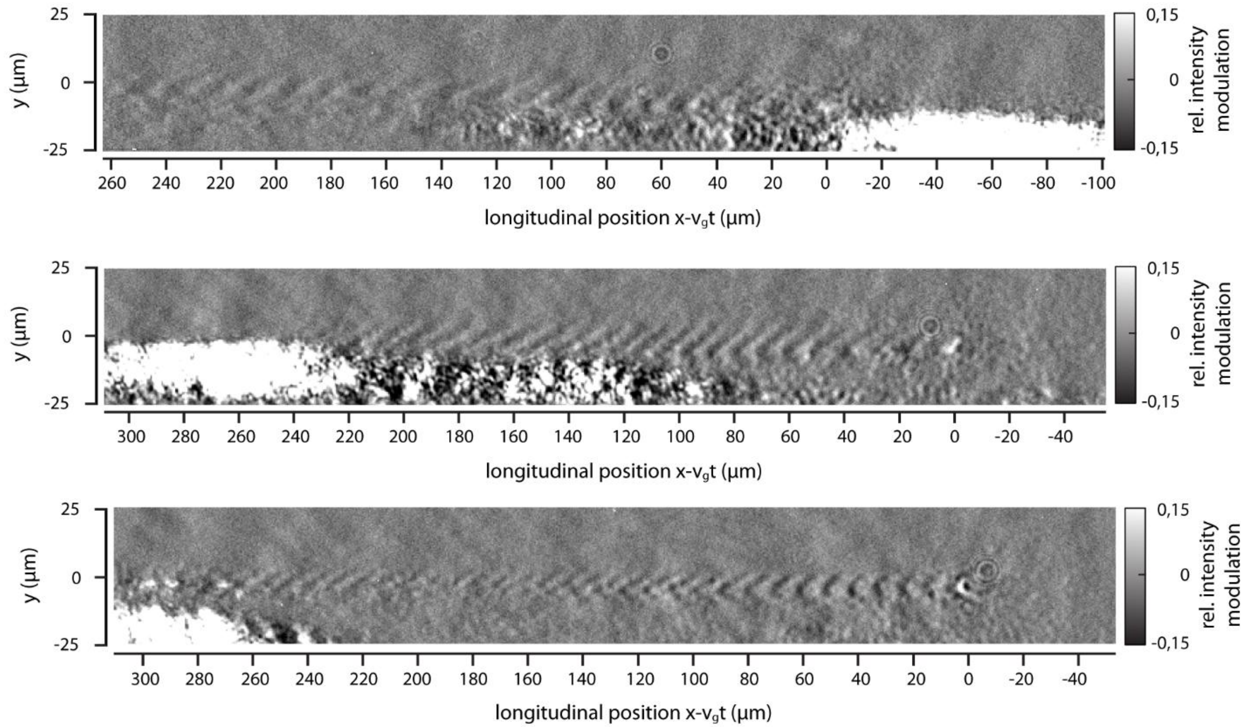


Excitation of asymmetric plasma waves

Stimulated side scattering



Transition from linear to nonlinear regime



$v_g t = 390\ \mu m$

$n_e = 1.65 \times 10^{19}\ cm^{-3}$

$v_g t = 520\ \mu m$

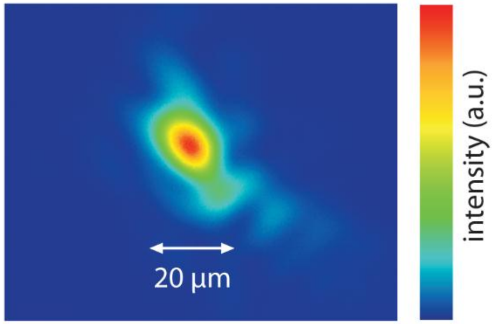
$v_g t = 590\ \mu m$

Pulse front tilt & mismatch

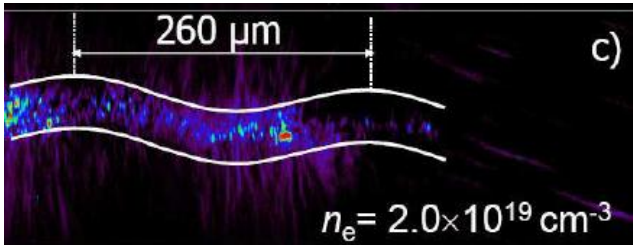
Pump amplification & wavefront rotation

Blowout

Laser hosing instability

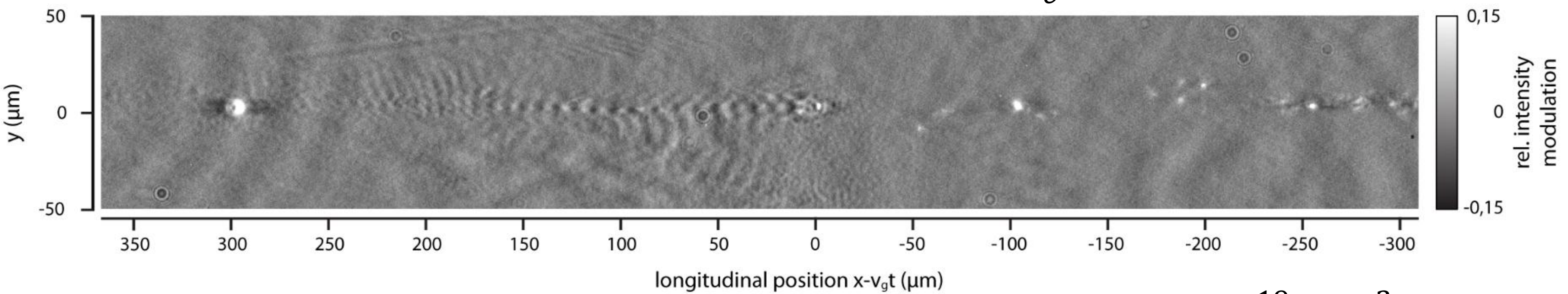


spatial temporal asymmetry

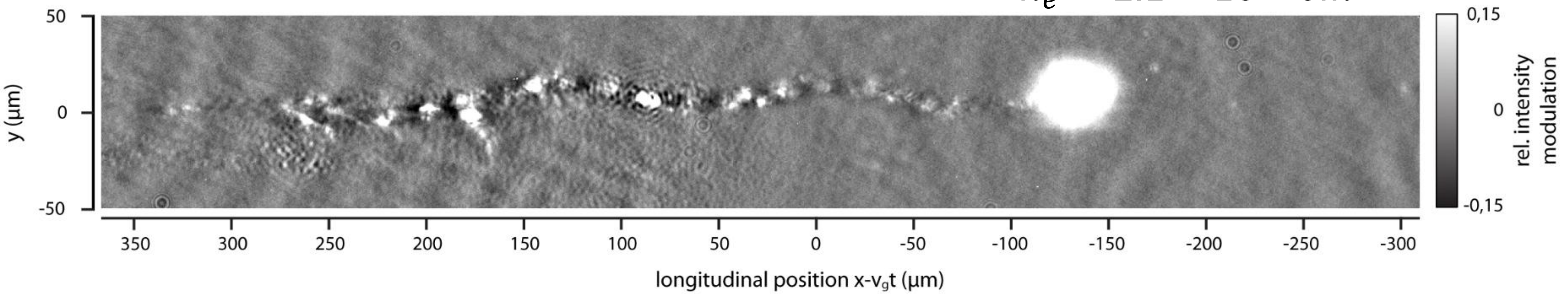


Kaluza *et al.*, Phys. Rev. Lett. **105**, 095003 (2010)

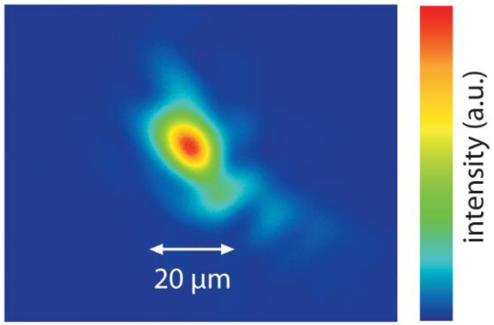
$n_e = 1.65 \times 10^{19}\ cm^{-3}$



$n_e = 2.1 \times 10^{19}\ cm^{-3}$



Laser hosing instability - evolution

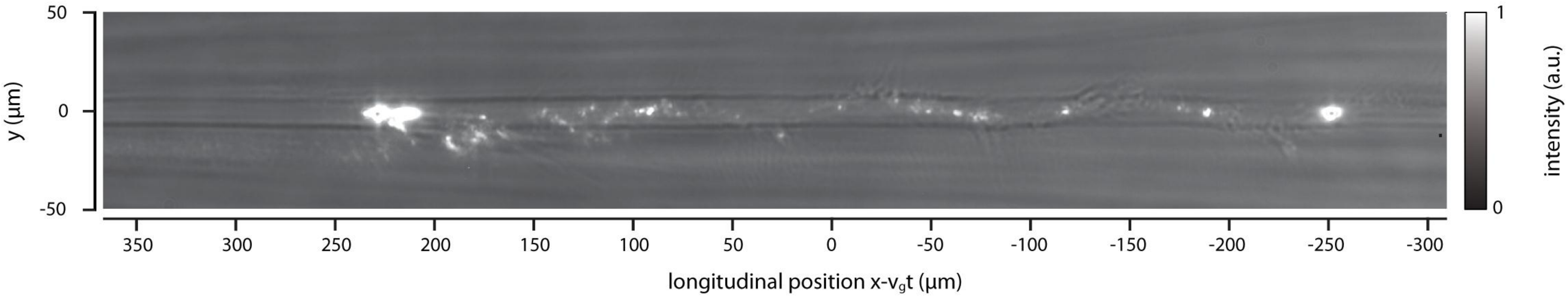


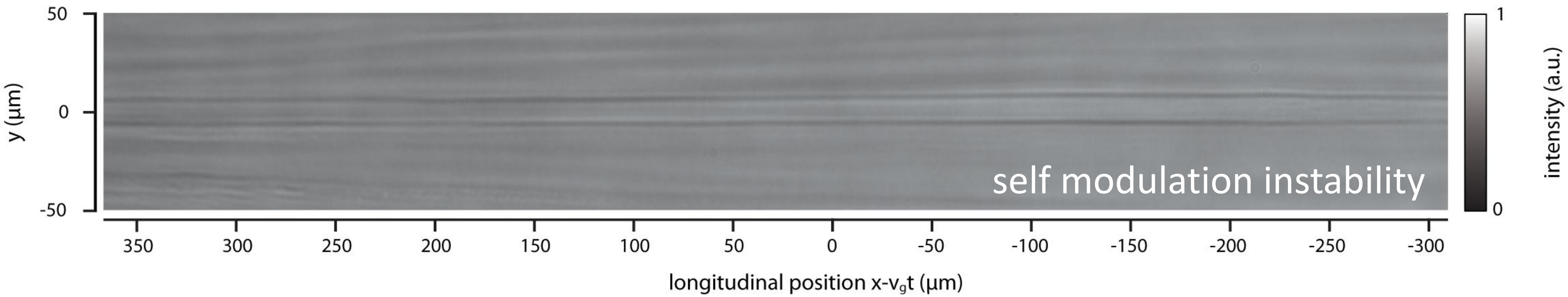
spatial temporal asymmetry

- Important at long interaction length

Kaluza *et al.*, Phys. Rev. Lett. **105**, 095003 (2010)

$$n_e = 2.2 \times 10^{19}\ cm^{-3}, \Delta\tau = +6.6\ ps$$





Summary & Outlook

- *Few cycle microscopy* is a very powerful diagnostic tool for (laser) plasma interactions

- *Few cycle microscopy* reveals the transformation of the plasma wave during formation, injection and acceleration

- Experimental observation of bubble expansion in the self-injection regime leading to injection of electrons into the wakefield

- Benchmark PIC codes by investigating instabilities

Very interesting times ahead!

Probing future wakefield accelerators

Energy gain

$$\Delta E[GeV] \cong 1.7 \left(\frac{P[TW]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_p[cm^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda_0[\mu m]}\right)^{4/3}$$

W. Lu et al. Phys. Rev. ST Accel. Beams 10, 061301

lower plasma density

↓

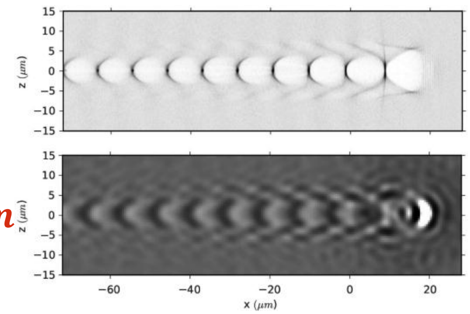
lower plasma frequency

JETi 200: $P = 200\ TW,$
$\tau_L = 17\ fs$
pulse duration: $\tau_L \leq \lambda_p/2$

JETi40

$n_p = 1.6 \times 10^{19}\ cm^{-3}$

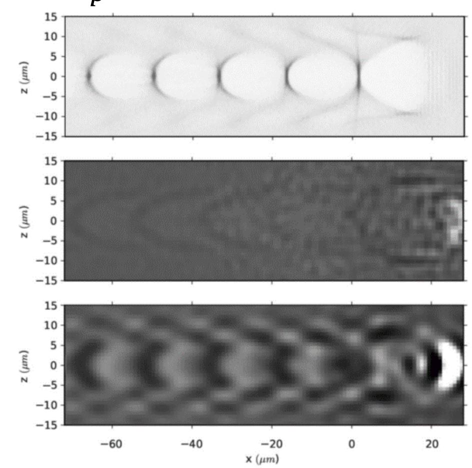
$\lambda_p = 750\ nm$



JETi200

$n_p = 0.4 \times 10^{19}\ cm^{-3}$

$\lambda_p = 1.4\ \mu m$

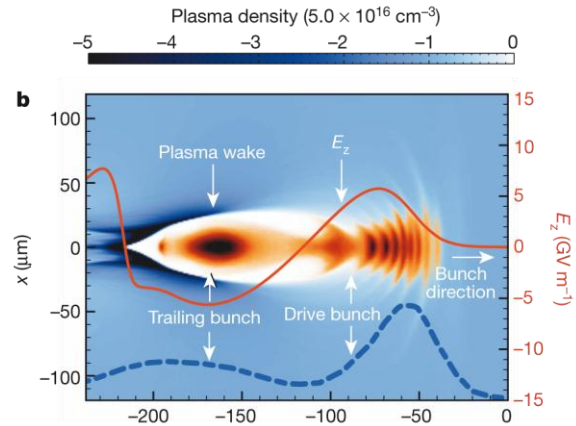


For probing techniques, the refractive index $n = \sqrt{1 - \frac{\omega_p^2}{\gamma \omega_{probe}^2}}$ defines the sensitivity!

Few cycle light sources in the MIR

$n_e = 7 \cdot 10^{18}\ cm^{-3}$

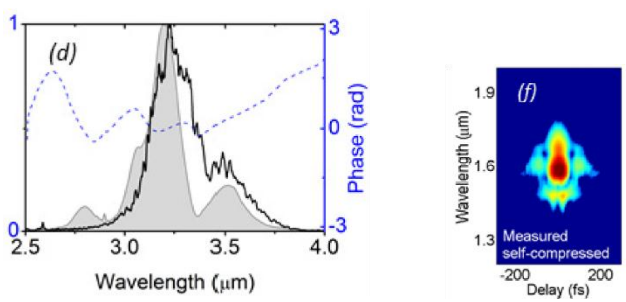
$\lambda_{probe} = 750\ nm$



M. Litos *et al.* Nature **515**, 92 (2014)

$\lambda_{probe} = 8\ \mu m$ required

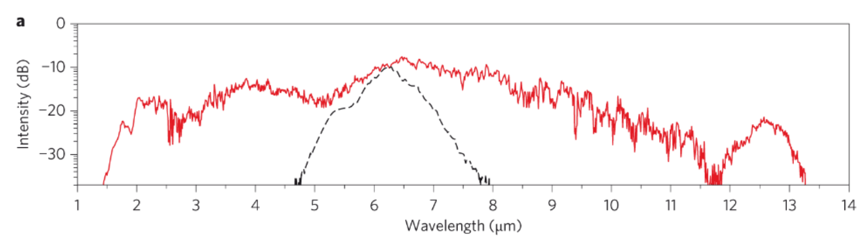
Sub 3-cycle laser pulses @ $\lambda_c = 3.1\ \mu m$



$E_{pulse} = 10\ \mu J\ @\ 160\ kHz$

M. Hemmer *et al.* Optics Express **21**, 28095 (2013)

Super continuum @ $\lambda_c = 6.5\ \mu m$



$E_{pulse} = 100\ nJ\ @\ 1\ kHz$

C.R. Petersen *et al.* Nat. Photon. **8**, 830 (2014)

All optical techniques like shadowgraphy (imaging wakefields), polarimetry (imaging magnetic fields) are feasible for PWFA experiments!

Thanks to all collaborators

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